

**THE INTERSTELLAR MEDIUM
AND DISK-HALO INTERACTION OF
THE EDGE-ON GALAXIES NGC 3044 AND NGC 5775**

by

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presented to the Department of Physics
in fulfilment of the
requirement for the degree of
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Abstract

This thesis studies the interstellar medium (ISM) and the disk-halo interaction of two spiral galaxies, NGC 3044 and NGC 5775. These two galaxies are both edge-on and infrared-bright, but NGC 3044 is isolated and NGC 5775 is currently interacting with a companion. We found HI supershells in both of these galaxies. The purpose of this study is to examine the different components of the ISM, to compare their distributions within each galaxy, to relate the ISM to the formation of supershells and to test the ISM disk-halo model envisaged in Norman and Ikeuchi (1989). Such a comprehensive study of the ISM in galaxies known to host large-scale structures has never before been done. Our work therefore contributes to the understanding of the formation of these structures with respect to the global structure of the ISM. We have found large-scale vertical structures of neutral hydrogen gas emerging from the disk of both galaxies.

We have obtained observational data which trace the distributions of the different components of the ISM, including emission from neutral hydrogen, molecular gas, energetic cosmic rays, dust and ionized gas. For both galaxies, we find normal global ISM parameters such as total mass, density, luminosity and star formation rate (SFR) for starburst galaxies of their class (SBc), in spite of the existence of a global asymmetry in the gas distribution in NGC 3044 and the current interaction of NGC 5775 with its companion. This indicates that the formation of large-scale structures does not require extreme conditions, since these galaxies are normal by all account.

We found expanding supershell signatures in 4 of the high latitude features in

NGC 3044 and 2 in NGC 5775. Assuming a one time energy injection by supernovae at the centre of an expanding feature, most of the expanding features would require the equivalent of tens of thousands of supernovae. For both galaxies, we show that the current SFR and available $H\alpha$ luminosity do not preclude the existence of supergiant star clusters that can produce this many supernovae. However, the largest super star clusters observed in some galaxies contain a factor of 2-3 less massive stars than required to form the largest supershells in the two galaxies study here. We suggest that assistance from instability of magnetic field lines may be necessary to alleviate the extreme energy requirements. For NGC 3044, the formation of supershells by impacting clouds may be ruled out based on the ages of the supershells and the lack of a source of high velocity clouds around the galaxy. For NGC 5775, at least 2 high-latitude features are related to the neutral hydrogen bridge connecting it with its interacting companion. However, some of the other features strongly indicate an internal origin. For this galaxy, a combination of cloud impacts and massive stars may be working together to produce the high-latitude features observed.

An ISM disk-halo interaction model proposed by Norman and Ikeuchi (1989) envisages the ISM of a galaxy to be in one or more of three stages: the three-phase stage, in which hot gas fills the ISM; the Chimney stage in which hot gas fills only a small volume of ISM via the channels provided by the hollow and broken-topped supershells (the so-called Chimneys); and the two-phase stage in which the supershells are not able to break out of the neutral gas layer. By constraining the degree of clumping of supernovae in OB associations and the ambient gas density, the model predicts that both galaxies are very likely to be in the Chimney phase, consistent with what we would infer from the fact that supershells are observed.

Statement of Originality

The contents of this thesis are solely the work of the author, under the supervision of Dr. Judith A. Irwin, except for the following: The ^{12}CO $J=1\rightarrow 0$ data for NGC 5775 were obtained and reduced (but not analyzed) by Götz Golla. The HI results were taken from Irwin (1994) with permission. The radio continuum results were obtained from Sorathia (1994) for NGC 3044 and Duric *et al.* (1997) for NGC 5775 with permission. The HIRES images were product of the Infrared Processing and Analysis Center (IPAC) in Pasadena California. The $\text{H}\alpha$ images were supplied by R. Grashuis and N. Duric (for NGC 3044) and R.-J. Dettmar (for NGC 5775).

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¹National Aeronautics and Space Administration

²Infrared Processing and Analysis Center

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Chapter 1

Introduction

1.1 General Structure of the Interstellar Medium

The disks of spiral galaxies are vibrant places containing stars, gas, dust, and energetic particles. The evolution of a galaxy depends critically on the structure of the interstellar medium (ISM) and the interactions amongst the different components of the galaxy. For example, a galaxy undergoing a “burst” of star formation (i.e., a starburst galaxy ¹) has more gas and dust compared to one which is relatively quiescent. The structure of the ISM, in turn, is shaped by the life cycle of stars (especially massive stars), from star formation, which extracts gas from the ISM, to supernova explosions, which recycle gas back into it. This life cycle not only enriches the ISM with heavy elements but also releases great amounts of energy to shape the ISM. Thus, the study of the ISM plays a pivotal role in understanding the formation and subsequent evolution of galaxies. Naturally, the study of the ISM starts with our own Galaxy.

Our view of the structure of the ISM in the Milky Way galaxy has undergone a major revolution in the early seventies. The initial two-phase model proposed by Field *et al.* (1969) where the ISM is dominated by a cold ($T < 100$ K) neutral medium (CNM) and a warm ($T \sim 8000$ K) neutral medium (WNM) depicted a static

¹A *starburst* galaxy is defined here as one which has a far infrared luminosity, $L_{FIR} > 10^{10} L_{\odot}$

system where the two components are in pressure equilibrium. With the detection of the soft X-ray background (e.g. Williamson *et al.* 1974) and the O VI absorption lines (e.g. York 1974) indicating the existence of a hot ($T \sim 10^6$ K) component, the two-phase model gave way to the three-phase model presented by McKee and Ostriker (1977). This model envisaged the hot, low density ionized medium (HIM), which is the result of supernovae explosions, permeating the disk while the CNM and WNM are embedded in the HIM. In this model, the WNM is thought to surround the CNM as a warm envelope. The outermost layer of the WNM is ionized by the interstellar radiation field to form the warm ionized medium (WIM). The WIM is usually considered as part of the HIM and hence does not constitute a separate component. More recently, the CNM has also been used to refer not only to the neutral atomic hydrogen (HI) component but also the molecular gas component as well. The three-phase model serves to represent an ISM which is dynamic rather than static, a concept which is more intuitive considering the effect of the enormous amount of energy from supernova explosions.

Although most researchers generally accept the idea of a three-phase ISM, the detailed picture of how these different components are inter-related is still being debated. In particular, the volume filling factor of the hot component is very uncertain. For example, Cox and Smith (1974) suggested that the hot gas resides in what they called “tunnels” (the overlapping regions of two or more supernova remnants) and fills only 10% of the disk. McKee and Ostriker (1977), on the other hand, predict the HIM to fill roughly 70% of the volume of the Galaxy. Observationally, it has been established that the Sun is located inside a local hot X-ray bubble about 100 pc in radius. However, the filling factor of the hot gas in the whole galaxy cannot be pinned down easily. Various numbers were obtained by different observers ranging from 2%

up to 40% from O VI absorption line studies (see e.g., Jenkins 1977, Labov 1988). The CNM, being concentrated into clumps, has a very small filling factor ($\sim 1\%$). The WNM fills $\gtrsim 15\%$ of the ISM (Jahoda *et al.* 1985, Braun and Walterbos 1992) and there is evidence that it is filamentary or sheet-like in structure (see images in Heiles 1979), although how much of that is due to projection effects is difficult to say.

The vertical distribution of the various components of the ISM is summarized in McKee (1990). The distributions of the molecular gas and the HI (constituting the CNM) are each described by a Gaussian with small scale height (~ 60 and 100 pc, respectively); the WNM distribution is the sum of two components, a Gaussian with a scale height of about 200 pc and an exponential with a scale height of 480 pc (Lockman 1984, Tenorio-Tagle and Bodenheimer 1988). The WIM distribution is the sum of two exponential components with scale heights of < 70 pc and about 1 kpc (also known as the Reynolds layer, see Reynolds 1989), respectively. Finally, an exponential distribution with scale height of about 3 kpc probably best describes the HIM (Savage and Massa 1987).

From these scale heights, we can see that the warm components extend to the base of the halo, which we defined it to be above roughly 1 kpc from the midplane while the hot component is part of the halo. If confinement is insufficient, the hot gas can overcome the gravitational potential and escape in the form of a galactic wind (Heckman *et al.* 1990). Shapiro and Field (1976) proposed, instead, that the hot gas will cool radiatively on a timescale of $\sim 10^7$ years as it rises up and condenses into cool clouds. These cool clouds subsequently fall back onto the disk as high-velocity clouds (HVCs). This scenario is termed the “galactic fountain” model. Since Shapiro and Field’s work, various other authors have proposed variations on this theme, generally described as “circulation models” (e.g., Bregman 1980, Norman

and Ikeuchi 1989). Whether there are winds or disk-halo circulation, such disk-halo interaction is a dynamic process and, if true, will have a major effect on the evolution of a galaxy.

1.2 Observational Evidence of Disk-Halo Interactions

A rich variety of features are found in the Milky Way Galaxy; they range from filaments and arcs to bubbles and shells. Here, a few interesting examples are listed. The local hot X-ray bubble within which the Sun resides was mentioned above. Radio continuum Loops I to III (Quigley and Haslam 1965) trace three circles in and cover a third of the sky. The famous North Polar Spur (NPS), a radio-continuum protrusion stretching 120° over the Galactic pole, makes up the brightest section of Loop I, the largest loop. Soft X-ray emission was observed by several groups (Bunner *et al.* 1972, de Korte *et al.* 1974) from Loop I, suggesting a supernova remnant-related origin.

HI shells, supershells and “worms” were reported by Heiles (1979, 1984). These shells have radii ranging from 10 - 2000 pc. Some of them appear to decrease in angular size with increasing velocity, indicative of expansion motions. The expansion velocities range from 10 - 24 km s^{-1} . Using the estimated shell masses (M_{sh}) and the shell expansion velocities (V_{sh}), the kinetic energies (E_K) of the *expanding* shells are found to be between 10^{51} to 10^{54} ergs ($E_K = \frac{1}{2} M_{sh} V_{sh}^2$). Based on the assumption that each shell is produced by a one time energy injection at the centre, Heiles calculates the energy required to form each shell to be within 10^{52} to 10^{55} *ergs* and refers to shells that require $\gtrsim 3 \times 10^{52}$ ergs to produce as “supershells”. Worms depict small-scale vertical structures that emerge perpendicular to the galactic plane. Heiles

identifies the worms, which are found exclusively within the solar circle, as the “walls” of open-topped shells through which hot gas can funnel into the halo. More recently, Normandeau *et al.* (1996) has reported the discovery of a “chimney” feature in the Perseus spiral arm in the Galaxy. This chimney structure is a cone-shaped cavity in the HI emission map of the region situated north of the open cluster OCl 352, which has nine massive O stars. The authors found that the age of the cavity, calculated based on the assumption that it is carved out by stellar winds, agrees roughly with the age of the open cluster. This strongly suggest that the open cluster is the cause of the cavity.

If the Heiles shells and supershells result from starburst activity, then they, as with the case of the cavity mentioned above, should be spatially correlated with “population I” objects such as HII regions, OB associations and supernova remnants. In fact, not all of them can be linked to nearby population I objects. Quite to the contrary, most of the Heiles supershells are located outside the solar circle where population I objects are scarce. Also, some supershells are found to be related to high-velocity clouds (HVCs) associated with the Galaxy (Mirabel 1989). HVCs are neutral cloud complexes observed in the 21-cm line either in emission or absorption. Their radial velocities are $\gtrsim 90 \text{ km s}^{-1}$ and are usually negative with respect to the Galactic standard of rest, which means most of them are probably falling onto the Galactic disk. Due to our position in the Galaxy, distance estimates of the HVCs are extremely uncertain, which makes estimating their sizes, masses and deducing their origin very difficult. If these HVCs do indeed interact with the Galactic disk, then depending on their masses and velocities, then they (rather than supernovae and stellar winds) may easily have created the supershells above (Tenorio-Tagle 1981, Rand and Stone 1996). We will elaborate on these two possible origins in § 1.3.

Besides the Milky Way, many other late-type galaxies display similar features. Many shells and supershells with diameters ranging from 600 - 1400 pc were discovered on H α plates of the Large Magellanic Cloud (LMC) by Meaburn (1980). It is believed that these shells are produced by stellar winds and supernovae from the observed OB associations within the shells (e.g., Dopita *et al.* 1985).

HI observations of M31 revealed over a hundred complete or partial “holes” in the HI distribution (Brinks and Bajaja 1986). These holes, which have diameters between 100 to 1000 pc, are interpreted as open-topped shells much like those in the Milky Way Galaxy but seen face-on (Brinks and Bajaja 1986). Under the same assumption as in Heiles (1979) (see above), the authors found that the energy required to create these holes ranges from 10^{49} to 10^{53} ergs. In NGC 4631, an edge-on, interacting galaxy, two expanding HI supershells were discovered. They have diameters and expansion velocities of 2.8 kpc, 45 km s $^{-1}$ and 1.8 kpc, 35 km s $^{-1}$, respectively (Rand and van der Hulst 1993). Rand and Stone (1996) proposed an impacting cloud origin to these supershells, based on the fact that tidal debris is probably plentiful around this interacting galaxy.

In NGC 891, numerous vertical dust filaments were seen silhouetted against the diffuse ionized gas in this edge-on galaxy (Keppel *et al.* 1991) (see Fig. 1.1). A vertical molecular spur reaching up to 520 pc above the disk was also discovered by Handa (1992).

A number of HI supershells were found in NGC 1313, a southern barred spiral. The largest of these has a diameter of about 3 kpc and requires about 10^{54} ergs of energy to form (Ryder 1995). The authors rejected impacting clouds as the formation mechanism because this supershell displays both the receding and approaching hemispheres indicating that it has not broken out of the HI disk and therefore must have

originated near the midplane of the galaxy. A number of HI supershells were also discovered in the edge-on galaxies NGC 3079 (Irwin and Seaquist 1990), NGC 5775 (Irwin 1994) and NGC 3556 (King and Irwin 1997); and the list goes on. Note that HI supershells have mostly been found in *edge-on* galaxies because of their orientation.

At least some super-structures listed above are seen to extend into the lower halo of their host galaxies. Combined with other observations, for example the existence of a thick ionized disk (Rand *et al.* 1992) or a thick radio-continuum disk (Sorathia 1994), these galaxies clearly exhibit some kind of disk-halo interaction. In this thesis, only one aspect of the disk-halo interaction, namely, the formation of the high-latitude HI supershells, will be singled out for a detailed study.

1.3 The Origin of Supershells – Two Popular Models

The origin of the HI shells and supershells are of considerable interest because these structures evidently have a significant effect on the ISM. Two most plausible explanations to their origin have been proposed, namely, the combined effect of stellar winds and supernovae explosions and the consequence of impacting clouds (see Tenorio-Tagle and Bodenheimer 1988 and references therein for a review to this date). In the following, I shall review the basic ideas of these two models.

1.3.1 Stellar Winds and Supernovae Explosions

On a scale of about 100 pc or so, dense regions known as Giant Molecular Clouds (GMCs) are found in the CNM. Within these GMCs are cloud cores where stars, usually in clusters, are being born.

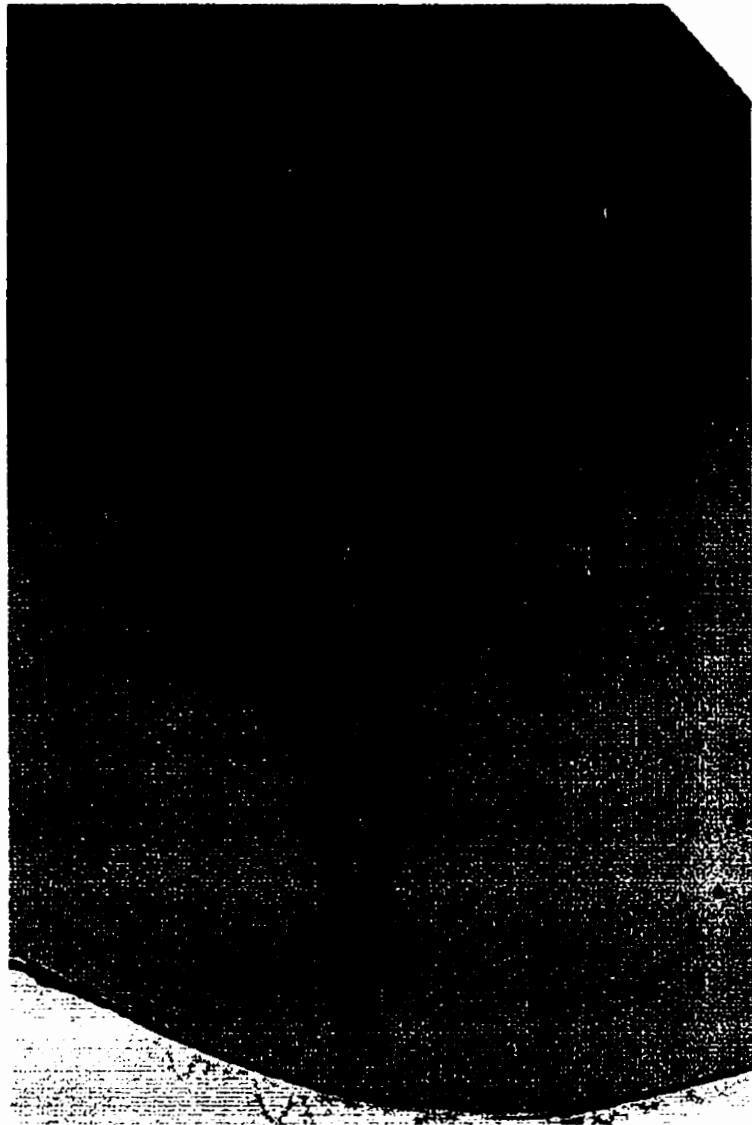


Figure 1.1: The continuum subtracted H α image of NGC 891. North is towards the upper right corner. The dust “worms” (wiggly white features standing vertically from the disk of the galaxy) can clearly be seen in the midplane of the galaxy as they obscure the dark H α emission. Adopted from Figure 1 in Keppel *et al.* (1991).

Regions such as the Orion cloud core contain loosely clustered young, massive O and B stars called OB-associations. These massive stars live relatively short (10^6 to 10^7 years) but brilliant lives. They emit energetic photons which ionize the gas surrounding them, carving out bubbles of HII regions a few pc in radii and with typical temperatures of 10^4 K. During their lifetime, the OB stars continuously lose mass in the form of high-velocity ($\approx 1000 \text{ km s}^{-1}$) stellar winds, which also contribute to the ionization of the surrounding gas as well as setting the gas in motion. Eventually, the OB stars extinguish after glorious displays of supernovae explosions. Each supernova releases about 10^{51} ergs of kinetic energy. Within a generation, an OB-association does not have enough time to leave the molecular cloud in which it was born, therefore, the supernovae explosions of the OB stars in the association are correlated in space and time, and conspire to disrupt the surrounding cloud.

Models to explain the formation of shells and supershells using stellar winds and supernovae exist in many variations. In general, these models propose that the observed shells are in fact swept up interstellar material when expanding supernova remnants enter from the energy-conserving phase (i.e., negligible radiative energy losses) into the momentum-conserving phase (the *snow-plough phase*). The shell is formed because the gas just behind the shock wave, caused by the initial explosion, begins to cool radiatively. Model parameters involved in such calculations include the number of OB stars in a cluster which, in turn, depends on the initial-mass function, the supernova rate, the supernova explosion energy, and the gas distribution of the ISM. Typical Galactic values are employed in most models; the total kinetic energy of the swept-up shell and the final radius of the shell are calculated in order to compare with those obtained for Heiles' shells.

Bruhweiler (1980) considered the effect of a typical Galactic OB association (they

used parameters for Sco OB1) on the evolution of a bubble. The bubble is initially formed during the stellar wind phase. By the time the 28 most massive stars exploded, this bubble has entered the momentum-conservation phase and swept-up a thin shell. In their calculation, the bubble is assumed to stay in this phase throughout its subsequent evolution. After about 10^7 years, the B0-B3 stars become supernovae and inject more energy into the remnant. An exponential HI distribution is assumed perpendicular to the galactic plane and three galactocentric radii (in the inner disk, solar circle and outer disk regions) were considered. By including the effects of gravitation in the direction perpendicular to the galactic plane, the author shows that the radius of the shell is larger parallel to the plane than the radius perpendicular to it. This is in agreement with the observations of shells in the Galaxy. By the time the shell velocity decreases to that of the random cloud velocities in the ISM, the shell radius range from about 200 to 700 pc, being larger at larger galactocentric distances. However, the modeled kinetic energies are at least an order of magnitude lower than those observed in Galactic supershells.

Tomisaka *et al.* 1981, in their numerical calculation, considered the evolution of a remnant in a constant density medium over a range of densities. They allow the injection of supernova energy to be at a range of fixed time intervals. In addition, radiative cooling of the remnant was included in their model. The final shell radii and kinetic energies obtained were, as in Bruhweiler (1980), small compared to the observed supershells. Only in the most extreme case (with very small density and large number of supernovae) did a supershell result. Numerical work by Mac Low and McCray (1988) shows that in a density-stratified medium perpendicular to the galactic plane, the portion of the remnant which accelerates to higher latitude where the particle density is lower will become Rayleigh-Taylor unstable. The result is

that shell fragmentation will occur and the shell will not remain in the momentum-conservation phase. If the original star cluster is located above the disk by more than 60% of the scale height, the shell will break open at the top allowing the hot gas to flow into the halo. This is called the *blow-out* condition (see Heiles 1990), although blow-out need not require that the energy source be above mid-plane (see Heckman *et al.* 1990 for superwinds). Seen face-on, these open-topped shells will resemble the HI holes found in M31.

More recently, Norman and Ikeuchi (1989) extended the “galactic fountain” model of Shapiro and Field (1976) to the “Chimney Model” in which they propose that the ISM of a galaxy evolves through the three-phase stage, the Chimney phase stage (see below) and the two-phase stage depending on the star formation rate (SFR) and the ambient density of the galaxy. The ISM of an active galaxy, such as a starburst galaxy or an active galactic nucleus (AGN), may be in the three-phase stage with the HIM occupying a large volume of space while the ISM of a quiescent galaxy such as a low-surface-brightness galaxy (Bothun *et al.* 1990) may be in the two-phase stage.

In the Chimney stage, spatially and temporally correlated supernova explosions from OB associations are the major source of energy input to the ISM. Large hot bubbles form and expand due to these supernovae and sweep up ambient material into thin shells. Depending on the scale height of the disk, the bubbles may break out of the thin disk providing channels (the chimneys) through which hot gas can escape into the halo. The edges of the largely neutral shells, if in the line-of-sight of an observer, will appear as vertical features standing above the disk (walls of the chimneys). The HI “worms” discovered by Heiles (1984) are identified as such features. In this scenario, the HIM in the galaxy will therefore be highly localized (hence a small filling factor) and distributed mainly along the disk. The hot gas that

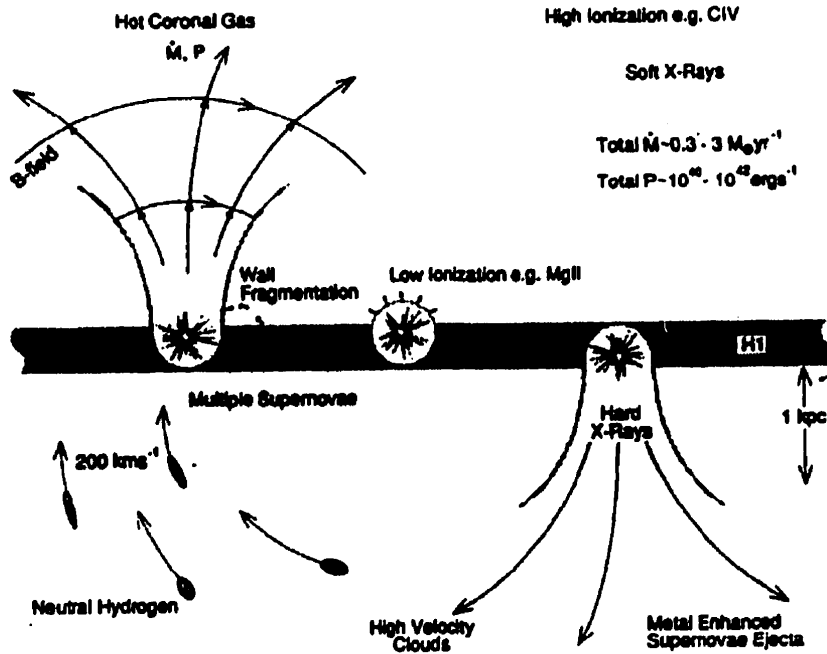


Figure 1.2: Schematic of the disk-halo interaction in a galaxy.

The horizontal grey strip represents the HI disk of the galaxy. The hot gas produced by multiple supernova explosions is able to reach the halo through the chimneys. The hot gas may eventually cool, condense and “rain” back down to the disk as high velocity clouds. Figure obtained from Norman and Ikeuchi (1989).

flows to the halo via “chimneys” will eventually cool at high-latitude and fall back onto the disk. A circulation of mass, energy and momentum is hence set up between the disk and the halo (Fig. 1.2). Given the correlated supernova rate and the ambient density of a galaxy, the Chimney Model can predict which one of the three possible stages (three-phase, Chimney or two-phase) a galaxy is in. The Chimney Model will be discussed in detailed in Chapter 6.

As successful as this class of models (i.e., disk origin models) is in explaining the formation of shells, it cannot be reconciled with the fact that large OB associations

are rare. The average number of massive stars in a Galactic OB association is <100 (Heiles 1990), with the largest one, the Sco OB association, containing about 200 of them. As stated above, the HI supershells in the Galaxy require upward of 10^{53} ergs to be produced (§ 1.2). If this input energy is supplied by supernova explosions, then a few thousand supernovae are required for the larger supershells. This situation is worst for the extragalactic supershells mentioned above, some of which require 10^{54} ergs of input energy. In addition, Heiles' supershells are mostly found outside the solar circle, where there are very few HII regions or OB associations. Other concerns about this class of model are 1) magnetic field confinement (which was omitted from many of the models) may prevent superbubbles from breaking out, hence no chimneys as described above will form (Salvin and Cox 1992) and 2) galactic rotation tends to shear the shells causing them to appear elongated (Tenorio-Tagle and Palous 1987b). The second point requires the supershells that appear circular in shape to be very young ($\sim 10^7$ years), which demands an even higher energy input rate, aggravating the already insufficient energy source.

1.3.2 The Impacting Cloud Model

Mirabel (1982) presented evidence of a connection between HVCs and an HI shell in the direction of the Galactic anticentre (the Anticentre Shell). He suggested that this shell is the result of a collision of HVC (from the Magellanic Stream) onto the galactic disk. The beauty of this possibility is that the impact of the cloud can inject kinetic energy of 10^{53} to 10^{54} ergs onto the disk, just the right amount needed for creating supershells. Meyerdierks (1991) show analytically that the North Celestial Pole HI loop and a complex of HI HVCs (called the Chain A Complex) may all be the result of the impact of a halo cloud onto the galactic disk.

When a cloud a few tens of pc across collides with the galactic disk, two shocks will result, one entering into the disk gas and the other away from the disk into the impacting cloud. Sandwiched between these two shocks is a layer of high temperature, compressed shocked gas (Tenorio-Tagle 1980). Numerical simulations (e.g., Tenorio-Tagle *et al.* 1987a) show that this shocked layer moves into the galactic disk and when the shock has cleared the cloud (i.e., at the end of the collision), the shocked gas begins to re-expand, filling the cavity carved out by the shock front with hot gas. As the shock front traverses the disk, shock compressed interstellar matter forms a thin shell just behind the shock (see Fig. 1.3). Formed this way, the shell would be expected to present a hemispherical shape rather than a complete shell. It is shown in these studies that a larger cloud and higher initial cloud velocity will result in a larger remnant with a more massive shell.

A requirement for this class of models is the existence of a source for the HVCs. Interacting galaxies should have no lack of such supplies, and the best example is the Milky Way Galaxy. Other possible sources of HVCs are primordial gas clouds and galactic fountains. The former are relic gas clouds left over from the period of galaxy formation (Spergel *et al.* 1996). However, positive detection of these have yet to be reported for external galaxies. The latter was proposed by Bregman (1980) for our Galaxy, where the HVCs are condensed gas originated from the hot gas from the disk. In any case, if HVCs with column densities of about 10^{20} cm^{-2} exist around galaxies, they should be easily detected with the sensitivity of modern radio arrays.

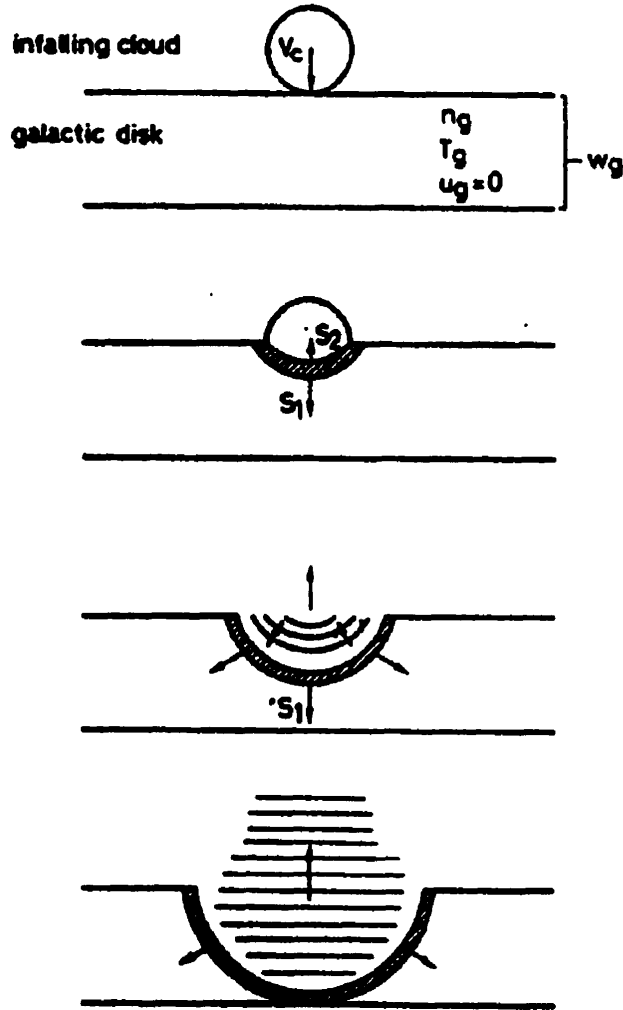


Figure 1.3: Illustration of the impact of a cloud onto the galactic plane. V_c is the velocity of the infalling cloud, n_g , T_g , u_g and w_g are the number density, temperature, velocity (which is at rest) and width of the galactic gas. S_1 and S_2 are the two shocks referred to in the text. The collision is over when the entire infalling cloud has been shocked (last panel). Diagram from Tenorio-Tagle (1980).

1.4 Summary and Discussion of This Project

Two decades after the discovery of the Galactic supershells, their formation mechanism remains a subject for debate. The two types of models discussed in the previous section each have their own drawbacks. The disk origin models predict input energies and kinetic energies which fall short by at least an order of magnitude from what is observed, except under extreme conditions such as very low density ISM or star formation rate that is much higher than observed. The impacting cloud models are successful in matching the size and energy requirements of supershells but require galaxies having supershells to be interacting in order to have a reservoir of infalling clouds. However, if it could be shown that isolated galaxies host supershells, then the impacting cloud scenario would be reduced to mere academic interest unless other sources for HVCs can be identified. Alternatively, other mechanisms may have to be invoked to explain supershell formation satisfactorily. For example, Kamaya *et al.* (1996), using a two-dimensional magnetohydrodynamic simulation, show that instead of confining the superbubble such as that proposed by Slavin and Cox (1992), supernova explosions can actually induce a Parker Instability (the undulation of horizontal magnetic field lines due to disturbance in the vertical direction). When the gas that was frozen at the “crests” of the field lines eventually drains to the troughs, the field lines will bulge upward (towards higher latitude) because the crests become lighter than the ambient material, giving rise to the blow out condition. Frei *et al.* (1997), suggest that the combination of differential rotation and the global magnetic field is capable of reproducing the sizes and kinetic energies observed in supershells, solving the energy problem.

Observationally, studies of the Galactic supershells are complicated by the distance

ambiguity problem due to the location of the Sun in the Galactic disk. This difficulty can be circumvented by observing supershells in external galaxies. The list of galaxies hosting HI supershells is slowly growing, but it is still too short for a full statistical study. Nevertheless, it would be extremely beneficial to learn whether there are any common traits these galaxies share and to compare the supershell parameters from the different galaxies. For example, if one subscribes to the impacting cloud idea, then one might expect only interacting galaxies to have supershells. At the initiation of this study, no isolated galaxy was reported to contain supershells. An isolated galaxy, NGC 3556, was subsequently discovered to have two large supershells (see chapter 7). On the other hand, if the massive star scenario is solely responsible, then starburst galaxies should be most likely to host these large structures. While many supershell galaxies are indeed undergoing starbursting, M31 and NGC 1313 are not, and the Milky Way can only be said to be actively forming stars and not strictly a starburst galaxy.

For this project, we have specifically chosen to study in detail the ISM and the HI supershells in two galaxies, NGC 5775 – a known *interacting* galaxy, and NGC 3044 – an *isolated* one. The supershells in NGC 5775 were reported in Irwin (1994) but detailed analysis of these objects was not done. Those of NGC 3044 are reported here for the first time (the results of which have recently been published by us in Lee and Irwin 1997). The detection of supershells in the isolated NGC 3044 is therefore of significance, in view of the lack of HVCs around this galaxy (see chapter 6). Other important attributes of these two galaxies are: they are infrared-bright and possess large radio-continuum halos (Sorathia 1994), both suggesting possible high star formation rates and hence allow us to test the disk origin models. In addition to HI, we

also investigate the distribution of the molecular component of the two galaxies using carbon monoxide emission data; high-resolution infrared (HIRAS) information is obtained from the Infrared Astronomical Satellite (IRAS) data; and radio-continuum data are obtained from Sorathia (1994) and Duric *et al.* (1997) with permission. Data in these different wavelengths are used to piece together the physical conditions in these two galaxies and provide some clues to the formation of the supershells.

The presence of supershells in these two edge-on galaxies as well as the large amount of data available for each render them good testing grounds for the ISM model envisaged by Norman and Ikeuchi (1989). We shall therefore compare the predictions of the Chimney Model to the observations to see how successful the model is.

The organization of this work is as follows: Chapter 2 presents all observations and data reduction methods. The results of the neutral hydrogen, carbon monoxide, radio continuum, infrared and ionized hydrogen data are presented in Chapter 3 for NGC 3044 and Chapter 4 for NGC 5775. As the discussion of the HI supershells of both galaxies constitutes a major part of this thesis, we devote Chapter 5 to it. Chapter 6 presents the discussions of the observations as well as the test of the Chimney Model. Finally, in Chapter 7, we give the concluding remarks and list future directions for this project. Note that throughout this work, the Hubble constant $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is used.

Chapter 2

Observations and Data Reductions

2.1 HI Observations and Data Reduction

NGC 3044 was observed in the HI 21cm emission line (at 1420.406 MHz) with the Very Large Array (VLA)¹ on June 19-20, 1993 in the C configuration. The VLA is a 27-element interferometer located at Socorro, New Mexico. The C-configuration has maximum and minimum antenna separations of 3.4 km and 73 m, respectively. The data were obtained during a remote observing session. Two flux (or primarily) calibrators, 3C48 and 3C286, and one phase (or secondary) calibrator, 0922+005, were observed. 3C48 was observed at the beginning and 3C286 was observed at the end of the observing session while the phase calibrator was observed approximately every half hour. Bandpass calibration was done using both primary calibrators. The data were Hanning-smoothed in frequency on-line. Parameters pertaining to the observations and mapping of NGC 3044 are listed in Table 2.1.

All data processing was done using the Astronomical Image Processing System (AIPS) developed at The National Radio Astronomical Observatory (NRAO). Data reduction was carried out following the standard procedure for interferometric data. A detailed discussion can be found in Perley *et al.* (1994), a brief outline is presented in Appendix A. Observation of NGC 3044 resulted in a total of 483,487 visibilities

¹Operated by Associated Universities, Inc. under contract with the National Science Foundation.

(see Appendix A) obtained during the observing session. We found the first 30 seconds of all scans (a scan is typically 24 minutes of observation) needed to be removed because the flux calibrations plotted for this time range are consistently low (not an unusual problem in interferometric observations) for all baselines. The flux densities of the calibrators were calculated using AIPS, which resulted in 16.09 Jy, 14.88 Jy and 0.75 Jy for 3C48, 3C286 and 0922+005, respectively. Thirty-three line-free channels were averaged together and subtracted from all 63 channels to obtain spectral line data alone. The routine MX (see Appendix A) was employed for mapping and deconvolution of the data cube. Two data cubes were obtained using MX, one using natural weighting and the other using uniform weighting. Both data cubes were corrected for primary beam attenuation using the task PBCOR. However, note that the target galaxy NGC 3044 occupies only about 6' at the centre of the field, hence the lower sensitivity at the outer edge of the field does not cause any problem in reality. In fact, the rms noise before and after primary beam correction differs by less than 5%.

The HI distribution of NGC 5775 was published in Irwin (1994). Observing parameters of this galaxy are also listed in Table 2.1 for completeness sake. The observation was done using the hybrid B/C configuration on July 16 - 17, 1989. The phase calibrator used was 1442+101 and the bandpass calibration was done using 0221+276. Data reduction was performed in a similar manner as described in Appendix A.

2.2 CO Observations and Data Reduction

NGC 3044 and NGC 5775 were observed in the ^{12}CO $J=2\rightarrow 1$, ^{13}CO $J=2\rightarrow 1$, ^{12}CO $J=3\rightarrow 2$, and ^{13}CO $J=3\rightarrow 2$ (NGC 5775 only) rotational transitions with the James

Table 2.1: HI Observation and Map Parameters

Parameter	NGC 3044	NGC 5775
VLA configuration	C	B/C
Observing date	1993 June	1989 July
On-source observing time (hours)	8.75	7.4
Approximate largest scale visible ^a (")	420	240
Primary beam FWHM	31'.4	31'.4
Band center ^b (km s ⁻¹)	1318	1600
Total bandwidth(km s ⁻¹)	1331	1291.7
Channel width (=resolution) (km s ⁻¹)	20.8	41.67
Synthesized beam parameters:		
Uniform weighting	13''.6 × 13''.5 @PA=-78°19	13''.6 × 13''.4 @PA=-33°7
Natural weighting	20''.7 × 20''.2 @PA=-29°54	28''.8 × 22''.8 @PA=52°0
Root mean square map noise:		
Uniform weighting (<i>mJy beam</i> ⁻¹)	0.61	0.50
Natural weighting (<i>mJy beam</i> ⁻¹)	0.45	0.40
Rayleigh-Jean conversion factor (<i>T_b/S</i>):		
Uniform weighting [<i>K(mJy beam</i> ⁻¹) ⁻¹]	3.30	3.36
Natural weighting [<i>K(mJy beam</i> ⁻¹) ⁻¹]	1.45	0.932

^a From Perley, 1994.^b Heliocentric, optical definition.

Clerk Maxwell Telescope (JCMT) ². Table 2.2 lists all the observing runs and transitions observed. Table 2.3 and 2.4 list all the positions observed for these two galaxies and the total integration time in minutes for each position. The positions are given as offsets in arcseconds in right ascension (RA or α) and declination (Dec or δ) with respect to the observing centre of each galaxy, positive values are to the east for RA offsets and to the north for Dec offsets. The centres of the galaxies used in the observations are: ($9^h51^m5^s0$, $1^\circ48'57''0$) for NGC 3044 and ($14^h51^m26^s8$, $3^\circ44'51''0$) for NGC 5775. Also included in Table 2.4 are the observations of the ^{12}CO J=1 $\rightarrow$ 0 transition obtained by Götz Golla during July 27-31 of 1990 using the 15-m Swedish-ESO Submillimetre Telescope (SEST).

At the JCMT, the front end receiver A2 (half-power beamwidth (HPBW) = $21''$) was used for the ^{12}CO J=2 $\rightarrow$ 1 and ^{13}CO J=2 $\rightarrow$ 1 line observations (see Matthews 1993). Receiver B3i (HPBW = $14''$) was used for most ^{12}CO J=3 $\rightarrow$ 2 (except during the service observing session on April 1997, which utilized the new receiver B3) and all ^{13}CO J=3 $\rightarrow$ 2 observations. A2 and B3i are single-channel heterodyne devices employing lead-alloy Superconductor-Insulator-Superconductor (SIS) mixers. Both operate in double-sideband mode (DSB). Receiver B3 (HPBW = $14''$) is a dual-channel (two mixers) heterodyne receiver newly installed at the JCMT to replace receiver B3i. It allows either single-sideband (SSB) or double-sideband operation. For the observations reported here, receiver B3 was tuned in the SSB mode. For the backend, the Dutch Autocorrelator Spectrometer (DAS) was used³. The DAS offers a channel-by-channel calibration (see Appendix B) which minimizes any line

²The James Clerk Maxwell Telescope is operated by The Observatories on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organization for Scientific Research, and the National Research Council of Canada.

³An autocorrelator spectrometer produces a power spectrum by performing a Fourier transform on the autocorrelation function of the input signal.

Table 2.2: Observing Dates at the JCMT

Dates	Galaxy Observed	Lines Observed
Jul 31 - Aug 6 1993	NGC 5775	$^{12}\text{CO } J=2 \rightarrow 1$, $^{13}\text{CO } J=2 \rightarrow 1$
Jan 30 - Feb 2 1994	NGC 5775	$^{12}\text{CO } J=2 \rightarrow 1$, $^{12}\text{CO } J=3 \rightarrow 2$, $^{13}\text{CO } J=3 \rightarrow 2$
Jan 13 1994 ^a	NGC 5775	$^{12}\text{CO } J=2 \rightarrow 1$
Feb 8 1994 ^a	NGC 5775	$^{12}\text{CO } J=2 \rightarrow 1$
Apr 4 - Apr 5 1994	NGC 3044	$^{12}\text{CO } J=2 \rightarrow 1$
Nov 26 - Nov 29 1994	NGC 3044	$^{12}\text{CO } J=2 \rightarrow 1$, $^{13}\text{CO } J=2 \rightarrow 1$, $^{12}\text{CO } J=3 \rightarrow 2$
Feb 4 - Feb 5 1995	NGC 5775	$^{12}\text{CO } J=2 \rightarrow 1$, $^{13}\text{CO } J=2 \rightarrow 1$
Apr 24 & Apr 25 1997 ^a	NGC 5775	$^{12}\text{CO } J=3 \rightarrow 2$

^aJCMT Service Observing time.

strength variations due to different bandpass gains as a function of frequency. The spectrometer bandwidth was chosen to accommodate the broadest line widths of the galaxies with extra frequencies on both sides of the spectra for baseline subtractions. In order to subtract the intensity contribution from the atmosphere, a technique called beam switching was used. The telescope beam points or switches between a blank position in the sky and the source of interest at a *chop rate* of 1 Hz. The angular separation between the blank sky position and the source is called the *chop throw*. For both galaxies, we observed with a chop throw of $180''$ in the direction perpendicular to the target galactic plane. For NGC 5775, this separation is sufficiently large to avoid emission from its interacting companion NGC 5774 as well as the HI bridges connecting them. Integration time for each scan varies, depending on sky conditions (longer integration time if sky is stable and shorter if not) but typically ranges from 300 to 900 seconds.

Table 2.3: CO Observations of NGC 3044

Transition (Frequency)	Offsets (arcsec)	Integration Time (mins)	Offsets (arcsec)	Integration Time (mins)
$^{12}\text{CO J}=2\rightarrow 1$ (230.538 GHz)	(0.0, 0.0)	59	(-7.8,-18.4)	40
	(31.5, -2.5)	30	(7.8, 18.4)	30
	(31.5, -2.5)	30	(7.8, 18.4)	30
	(18.4, -7.8)	20	(5.3,-13.1)	20
	(-18.4, 7.8)	30	(49.9,-10.3)	50
	(26.2, 10.6)	30	(57.2,-18.8)	40
	(-13.1, -5.3)	40	(75.6,-26.7)	40

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Transition (Frequency)	Offsets (arcsec)	Integration Time (mins)	Offsets (arcsec)	Integration Time (mins)
	(-5.3, 13.1)	20	(94.0,-34.5)	35
	(20.9, 23.7)	30	(112.4,-42.3)	40
	(44.6, 2.8)	30	(-23.7, 20.9)	10
	(36.8,-15.6)	20	(-34.9, 20.2)	30
	(23.7,-20.9)	30	(-53.3, 28.0)	20
	(10.6,-26.2)	40		
¹³ CO J=2→1 (220.399 GHz)	(13.1, 5.3)	80		
¹² CO J=3→2 (345.796 GHz)	(13.1, 5.3)	60	(6.7, 8.0)	40
	(0.0, 0.0)	10	(15.8, 11.7)	40
	(10.4, -1.1)	40	(16.8, -3.9)	40
	(19.6, 2.6)	40		

An absolute calibration is carried out at the JCMT by comparing the measured antenna temperature with that of two blackbody absorbers, one at ambient temperature and one at the temperature of liquid nitrogen. This process is called Three-load Calibration and is described in Appendix B. However, it is common to check the calibration against sources of known temperature during an observing run. Thus, standard sources were observed at the beginning and at the end of each observing session, as well as after switching receivers. Flux calibration sources used include CRL 2688, IRC+10216 and 16293-2422. In addition, the relative flux calibration

was also checked by observing the centre position in every session. In general, observed and archived (obtained from the JCMT website at www.jach.hawaii.edu/cgi-bin/standard.csh) spectra agree to within 20% in integrated intensity except on the following sessions (all of which were during observing runs for NGC 5775): Aug 3, 1993, the entire Jan 30 - Feb 2 1994 run and Feb 8 1994, when the integrated intensities were consistently lower by 27%, 40% and 46% respectively.

Table 2.4: CO Observations of NGC 5775

Transition (Frequency)	Offsets (arcsec)	Integration Time (mins)	Offsets (arcsec)	Integration Time (mins)
$^{12}\text{CO } J=1 \rightarrow 0$ (115.271 GHz) By G. Golla	(0.0, 0.0)	96	(-42.8, 24.2)	112
	(24.6, -36.5)	48	(6.4, -48.8)	48
	(-24.6, 36.5)	64	(-6.4, 48.8)	96
	(36.5, 24.6)	64	(12.3, -18.2)	48
	(-36.5, -24.6)	64	(-12.3, 18.2)	52
	(49.2, -73.0)	64	(36.9, -54.7)	36
	(-49.2, 73.0)	48	(-36.9, 54.7)	48
	(73.8, -109.4)	32	(18.2, 12.3)	48
	(-73.8, 109.4)	64	(-18.2, -12.3)	48
	(42.8, -24.2)	48		
$^{12}\text{CO } J=2 \rightarrow 1$ (230.538 GHz)	(0.0, 0.0)	158	(8.5, -30.5)	12
	(11.2, -16.6)	43	(19.7, -47.0)	12
	(-11.2, 16.6)	23	(33.6, -49.7)	12

continued on next page

Transition (Frequency)	Offsets (arcsec)	Integration Time (mins)	Offsets (arcsec)	Integration Time (mins)
	(2.7, 13.9)	28	(36.2, -35.9)	12
	(13.9, -2.7)	40	(38.9, -22.0)	12
	(-2.7, -13.9)	23	(-19.7, 47.0)	12
	(13.9, 2.7)	23	(-33.6, 49.7)	12
	(16.6, 11.2)	43	(-36.2, 35.9)	24
	(27.8, -5.4)	33	(-47.4, 52.4)	8
	(25.1, -19.3)	10	(18.2, 12.3)	35
	(-12.0, 0.0)	31	(36.5, 24.6)	30
	(22.4, -33.2)	15	(-6.4, 48.8)	30
	(5.4, 27.8)	25	(49.2, -73.0)	30
	(-16.6, -11.2)	32	(73.8, -109.4)	20
	(-5.4, -27.8)	22	(-49.2, 73.0)	20
	(-8.5, 30.5)	12	(-73.8, 109.4)	20
	(-22.4, 33.2)	12	(-18.2, -12.3)	20
	(-25.1, 19.3)	12	(6.4, -48.8)	20
¹³ CO J=2→1 (220.399 GHz)	(0.0, 0.0)	175		
¹² CO J=3→2 (345.796 GHz)	(-12.0, 0.0)	110	(-20.4, 12.4)	175
	(-1.6, -2.0)	50	(-14.0, -10.4)	50
	(-3.6, -12.4)	50	(-22.4, 2.0)	50

continued on next page

Transition (Frequency)	Offsets (arcsec)	Integration Time (mins)	Offsets (arcsec)	Integration Time (mins)
	(8.8, -4.0)	50	(5.0, 5.0)	40
	(0.4, 8.4)	50	(2.5, -7.5)	40
	(-10.0, 10.4)	50		
¹³ CO J=3→2 (330.588 GHz)	(-12.0, 0.0)	90		

The January 30 - February 2 1994 run was immediately after a telescope maintenance shift when receiver B3i had undergone a major overhaul. The main beam efficiency (η_{mb} , see Appendix B) of receiver B3i was measured on Jupiter during that particular observing run, we obtained $\eta_{mb} = 0.45$. This value is lower than the more typical value of 0.58 given by the JCMT Users' Guide (Matthews 1993). Since the measured η_{mb} accounts for all the losses except beam-source coupling, it was used to scale up the spectra. The reason for the lower intensities on Aug 3, 1993 and Feb 8, 1994 was unknown, and η_{mb} was not measured during these runs. However, we note that the line shape of the spectrum at the centre of the galaxy was not affected, we have therefore decided to scale the spectra according to the averaged ratio of the archived and observed calibration spectra (see below). During the Nov 26 - 29, 1994 and Feb 4 - 5, 1995 runs, $\eta_{mb} = 0.68$ and 0.74 were measured for receiver A2 using Mars. For receiver B3, $\eta_{mb} = 0.63$ was adopted (Avery, L., private communication). Observations of Jupiter, Mars, IRC+10216 and OMC1 (whichever was available during an observing session) were made approximately every 90 minutes to check on focusing and pointing.

2.2.1 Data Processing

Only spectra that were obtained under good conditions (i.e., pointing offsets within 4'' and focus within 15% of the observed wavelengths) were used. In all, less than 10% of all spectra were discarded based on these criteria. Data processing was done using the data reduction software, SPECX⁴. Each spectrum was first examined individually to remove any intensity spikes. Spectra were then averaged (weighted by system temperatures, T_{sys} , see Appendix B) so that there is one spectrum for each position observed. All averaged spectra were either fitted by linear baselines or, where necessary, polynomial baselines (approximately 30% of the spectra required polynomial baseline subtraction). Baseline subtraction is, to some extent, a subjective decision. We estimate, by subtracting different baselines to the spectra, that the uncertainty incurred by this process is generally no more than 15%.

If the integrated intensities (I) of the calibration spectra (we shall call these the reference spectra), taken at the beginning and at the end of each observing session, are consistently higher or lower than that of the archived spectra by more than 15%, then all spectra obtained during that session are scaled by a factor ($I_{standard}/I_{ref}$). The relative uncertainties in the integrated intensities due to this calibration process are then given by

$$\sqrt{\left(\frac{\sigma_{standard}}{I_{standard}}\right)^2 + \left(\frac{\sigma_{ref}}{I_{ref}}\right)^2}, \quad (2.1)$$

where $\sigma_{standard}$ and σ_{ref} are the standard deviations of $I_{standard}$ and the root-mean-square (rms) noise of the observed spectrum, respectively. It is found that in all cases, the relative uncertainties are about 15%.

The baseline-corrected and flux calibrated spectra were then binned to a velocity

⁴SPECX is written by Rachael Padman of the Cavendish Laboratory, Cambridge, U. K.

resolution of 8 km s^{-1} (from 0.8 km s^{-1}) to increase the S/N. Finally, all spectra were scaled to the main beam temperature with equation (B.14). A 5% uncertainty in the measurement of the main-beam efficiency (uncertainty quoted from the receiver fact sheets available from the JCMT website) is introduced when the spectra are scaled to the main-beam temperature.

Combining all of the above, it is estimated that the uncertainty of the integrated intensities (listed in Table 3.4 for NGC 3044 and in Table 4.5 for NGC 5775) is about 20%.

2.2.2 Data Sampling

The purpose of observing the different rotational transition lines of each galaxy is so that line ratios can be obtained, which will be used to find the physical properties of the molecular clouds in these galaxies. For NGC 3044, the $^{12}\text{CO } J=1 \rightarrow 0$ transition is obtained from published data (Solomon and Sage 1988) who observed NGC 3044 with the Five College Radio Astronomy Observatory (FCRAO) 14-m telescope (HPBW = $45''$). For NGC 5775, the $^{12}\text{CO } J=1 \rightarrow 0$ transition is obtained from SEST (HPBW = $43''$) (see Figure 2.1 for all observed positions). In order to obtain the $^{12}\text{CO } J=2 \rightarrow 1$ to $^{12}\text{CO } J=1 \rightarrow 0$ line ratios for both galaxies, the $21''$ JCMT beam must completely (i.e., the Nyquist frequency criterion is met) sample the area covered by the $43''$ SEST beam and the $45''$ FCRAO beam. Only then can the $^{12}\text{CO } J=2 \rightarrow 1$ data be smoothed to the larger $^{12}\text{CO } J=1 \rightarrow 0$ beams for comparison. Similarly, the $14''$ JCMT beam of the $^{12}\text{CO } J=3 \rightarrow 2$ transition must also sample the area covered by the $21''$ JCMT beam in order to obtain the $^{12}\text{CO } J=3 \rightarrow 2$ to $^{12}\text{CO } J=2 \rightarrow 1$ line ratios. To this end, we chose to observe, in $^{12}\text{CO } J=2 \rightarrow 1$, the central region of each galaxy in half-beam spacing while the regions outside of the SEST and FCRAO beam were sampled

Table 2.5: Radio Continuum Observations of NGC 3044

Wavelength (cm)		20	20	6
Array Configuration		C	D	D
On-source Time (mins)		50	65	62
Synthesize Beams (" × ") @P.A.(°)	Uniform	11.96×11.90 @ -44°29	48.65×47.01 @ -53°25	13.37×12.33 @ -63°85
	Natural	18.87×15.86 @ -7°11	55.62×55.16 43°46	18.77×15.17 7°63
rms Noise (mJy)	Uniform	0.081	0.101	0.058
	Natural	0.093	0.097	0.046

in one beam spacing (see Figures 2.2 and 2.4). For the ^{12}CO $J=3\rightarrow 2$ transition, positions observed are one half-beam apart and only the inner region of each galaxy is observed (see Figures 2.3 and 2.5). There are exceptions though. During one of the observing runs (Jan 30 - Feb 2 1994, for NGC 5775), the telescope pointing centre was specified incorrectly, causing all spectra observed during that run to shift in R.A. by $-12''$. However, during subsequent observing runs, we were able to compensate for this error by filling in the missed positions along the minor axis of NGC 5775. Also, the two outermost positions observed in NGC 5775 in ^{12}CO $J=2\rightarrow 1$ were chosen specifically to match that observed with the SEST. The ^{13}CO $J=2\rightarrow 1$ and the ^{13}CO $J=3\rightarrow 2$ transitions were obtained only at the centre positions of the galaxies.

2.3 Radio Continuum Data

Radio continuum maps of NGC 3044 are obtained from Sorathia (1994). Table 2.5 show the configurations and related map parameters.

20 cm radio continuum data for NGC 5775 were obtained from Duric *et al.* (1997).

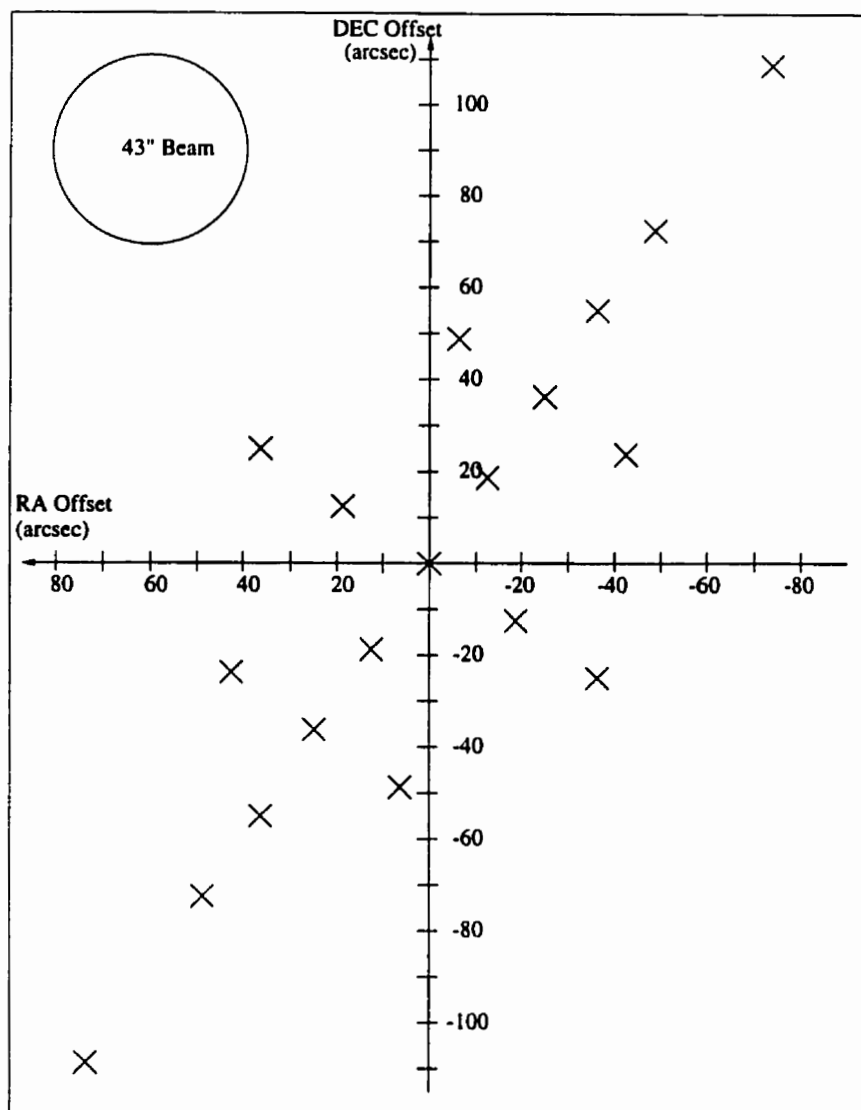


Figure 2.1: Observed ^{12}CO $J=1 \rightarrow 0$ positions of NGC 5775. A total of 19 positions are observed in the ^{12}CO $J=1 \rightarrow 0$ transition. The HPBW is shown as the circle on the upper left-hand corner. Positive offsets are east for the RA axis and north for the Declination axis. Note that the optical major-axis of this galaxy, at the 25th magnitude level, is $4''.2$.

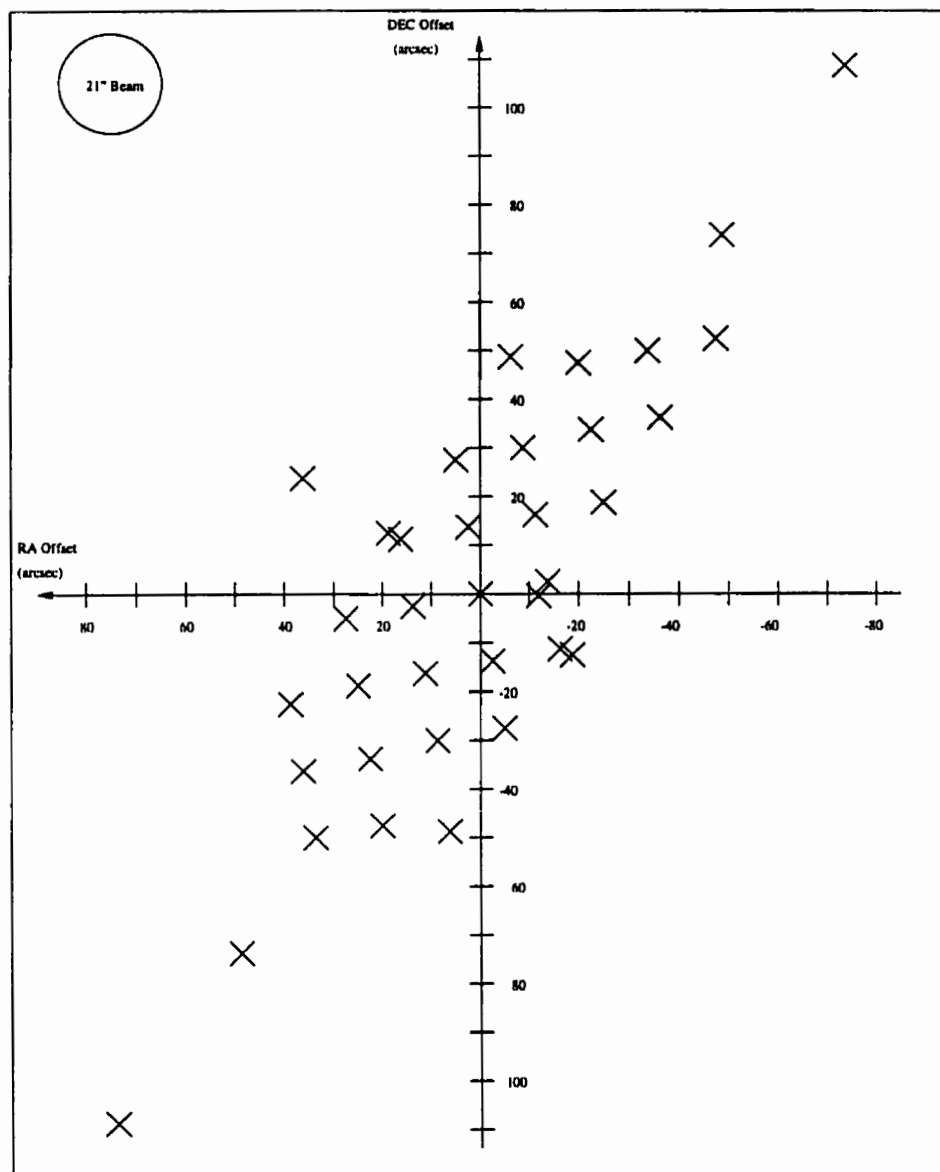


Figure 2.2: Observed ^{12}CO $J=2 \rightarrow 1$ positions of NGC 5775. A total of 36 positions are observed in the ^{12}CO $J=2 \rightarrow 1$ transition.

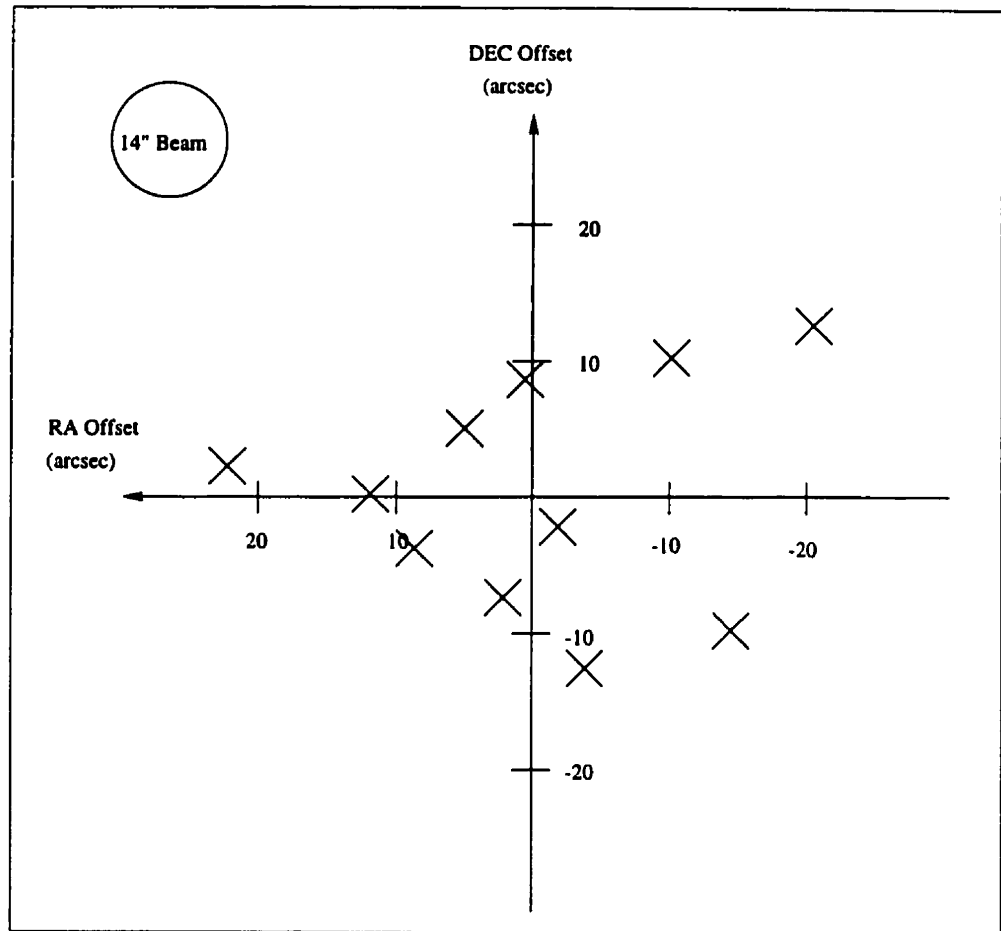


Figure 2.3: Observed ^{12}CO J=3 $\rightarrow$ 2 positions of NGC 5775. A total of 11 positions are observed in the ^{12}CO J=3 $\rightarrow$ 2 transition.

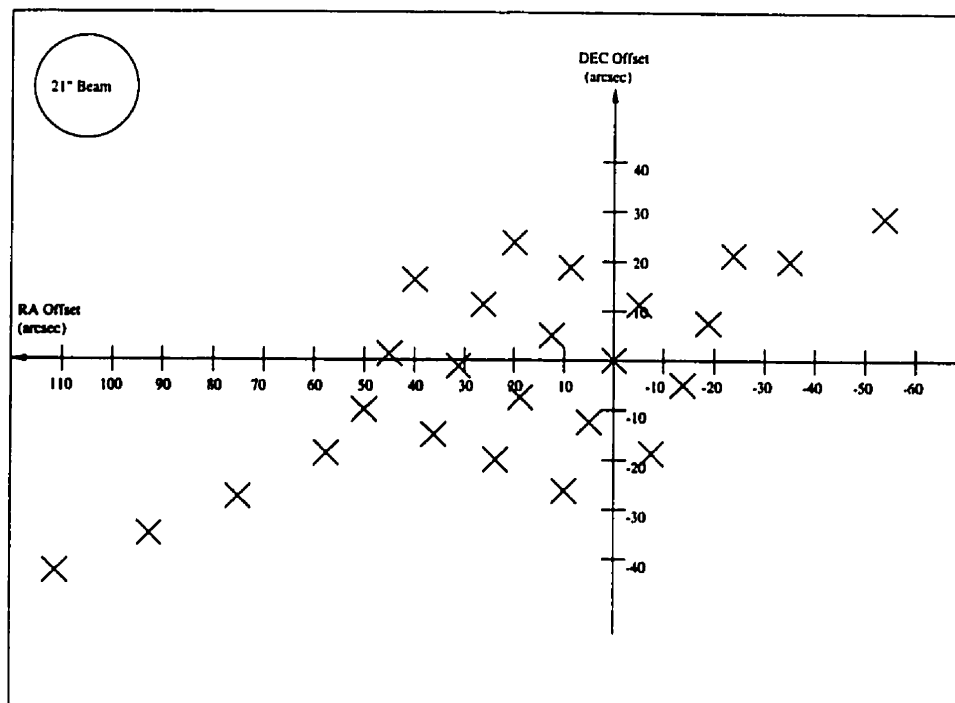


Figure 2.4: Observed ^{12}CO $J=2 \rightarrow 1$ positions of NGC 3044. A total of 25 positions are observed in the ^{12}CO $J=2 \rightarrow 1$ transition. The HPBW is shown as the circle on the upper left-hand corner.

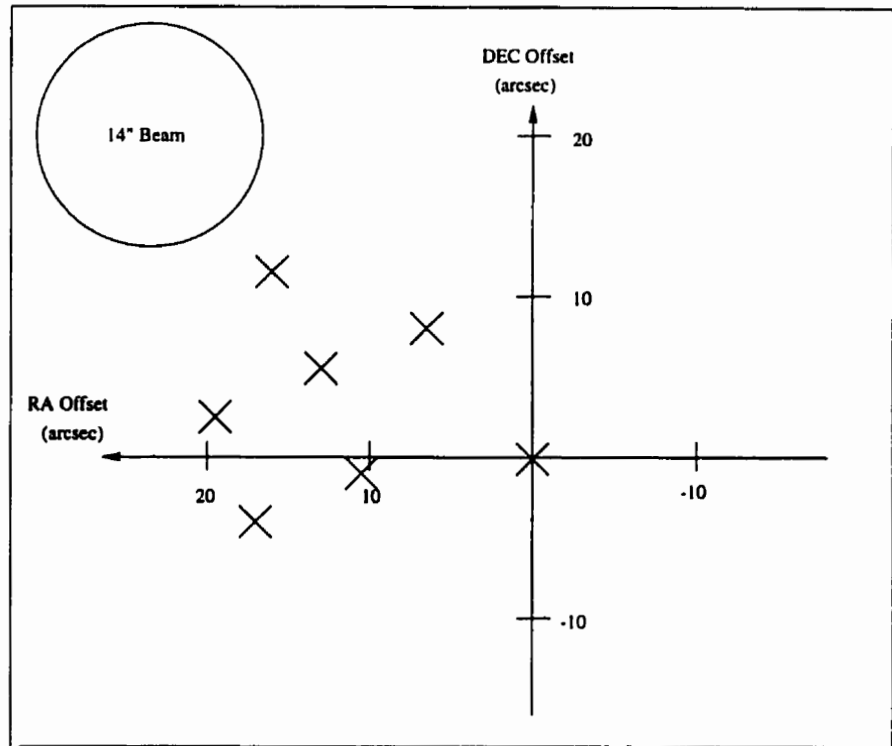


Figure 2.5: Observed ^{12}CO $J=3\rightarrow 2$ positions of NGC 3044. A total of 7 positions are observed in the ^{12}CO $J=3\rightarrow 2$ transition in order to fully sample the ^{12}CO $J=2\rightarrow 1$ beam at the (13.1,5.3) offset in Figure 2.4

The observations were made in the VLA B, C, and D configurations for a total observing time of 8 hours. The resultant maps have high sensitivity to large-scale structure from 300'' to 600'' corresponding to 36 kpc to 72 kpc in linear scale (rms map noise is $55\mu\text{Jy}$) as well as high resolution (synthesized beam of 5'').

2.4 High Resolution Infrared Astronomical Satellite Data (HIRES)

The processed HIRES data was obtained from the Infrared Astronomical Satellite (IRAS) database at the Infrared Processing and Analysis Center (IPAC)⁵ in Pasadena California. At IPAC, an image construction routine using the Maximum Correlation Method (MCM) (Aumann *et al.* 1990) was applied to the raw IRAS data to produce high resolution images. The MCM is an iterative process of obtaining the maximum number of uncorrelated pixels in the observed field. All maps shown here are the product of 20 iterations. For each band, a text file containing the effective beam sizes (beam major and minor axes HPBW's and position angles) sampled at 24 equally spaced pixel locations in the map is included in the finished product which was mailed to us electronically. Since the the HPBW's and position angles at the 24 locations all agree to within 10%, we simply take the mean values to be the beam HPBW's. Table 2.6 lists the HPBW and rms map noise for the 12, 25, 60 and $100\mu\text{m}$ bands of the IRAS for both galaxies. We also measured the rms map noise for each band by averaging the rms values of 4 or 5 background regions away from the source on the map.

⁵IPAC is operated by the California Institute of Technology, Jet Propulsion Laboratory under contract to the National Aeronautics and Space Administration (NASA).

Table 2.6: High Resolution IRAS Beams and RMS Map Noise

NGC 3044

Wavelength	Beam Size ($" \times "$)	Position Angle ($^{\circ}$)	Map rms (MJy/ster)
$12\mu\text{m}$	68.9×33.0	111.4	0.302
$25\mu\text{m}$	62.8×32.6	111.5	0.581
$60\mu\text{m}$	75.2×45.2	112.1	0.181
$100\mu\text{m}$	100.0×81.2	115.5	0.243

NGC 5775

Wavelength	Beam Size ($" \times "$)	Position Angle ($^{\circ}$)	Map rms (MJy/ster)
$12\mu\text{m}$	59.4×30.6	15.6	0.326
$25\mu\text{m}$	57.6×30.6	15.7	0.469
$60\mu\text{m}$	75.0×46.8	16.8	0.141
$100\mu\text{m}$	101.4×82.2	19.8	0.226

2.5 The $H\alpha$ Observations of NGC 3044 and NGC 5775

$H\alpha$ observations of NGC 3044 were obtained by R. Grashuis and N. Duric from the University of New Mexico. The images were taken at the Capilla Peak Observatory with the 0.6m telescope and a 512×320 CCD camera. The filter used was $H\alpha 657$ nm with an integration time of 1800 seconds. The pixel size is $0''.67$ on each side and seeing was about $3''$. Data reduction was done on-site and the images presented here are continuum-subtracted. The image is not flux-calibrated.

The continuum-subtracted $H\alpha$ image of NGC 5775 was obtained from R.-J. Dettmar (private communication). The image was taken with the European Southern Observatories 3.5m New Technology Telescope (NTT) on May 7, 1991 with a 1544×1244 pixel CCD camera. The pixel size is $0''.35$ square and seeing was about $1''.1$. Data processing and continuum subtraction were performed by Dettmar. The flux scale is not calibrated.

Chapter 3

NGC 3044

3.1 Introduction

NGC 3044 is an edge-on, SBc galaxy in the Leo Cloud (Tully 1988). The basic parameters, obtained from the RC3, are listed in Table 3.1. In their classification scheme for interacting galaxies, Solomon and Sage (1988) classify it as a Type I galaxy (i.e, second lowest level of interaction). This means that it has companions within $10D_{25}^1$ (0.31 Mpc in projection at the distance of the galaxy, see below), on the Palomar Sky Survey (POSS) print, with a velocity difference of less than 1000 km s^{-1} and showing no morphological disturbance. It therefore appears that this galaxy is not interacting with a neighbour. The optical image of NGC 3044 obtained from the Digitized Sky Survey² is shown in Figure 3.1. A dust lane (around $\alpha = 9^h51^m29.0$, $\delta = 1^\circ49'23''.5$) appears prominently on the northwestern (NW) side of the galaxy, obscuring part of the disk. Above the dust lane, a faint feature which protrudes to the NW away from the major axis appears to be the source of the classification by Sánchez-Saavedra *et al.* (1990) of the galaxy as having a “barely perceptible” optical

¹ D_{25} is the optical diameter of the galaxy at the 25th magnitude level.

²The Digitized Sky Survey as produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of this survey are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions.

Table 3.1: Basics Parameters of NGC 3044^a

Morphological Type	SBc(s)sp ^b
Right Ascension (α) (1950)	9 ^h 51 ^m 5 ^s .0
Declination (δ) (1950)	1°48'57".0
Optical Major $\times$ Minor axis	4'.9 $\times$ 0'.7
Heliocentric Velocity	1292 km s ⁻¹
Blue Magnitude	11.18

^aParameters obtained from the RC3

^bThis is the de Vaucouleurs classification scheme indicating a late-type Barred-Spiral with a general S-shape (s) and spindle (sp) structure.

warp. The feature curves the major axis in a counter-clockwise direction (inverse integral sign). On the southeastern (SE) side, the galaxy's optical disk fades out more gradually than the NW end, suggesting a possible asymmetric distribution of matter.

NGC 3044 was originally observed as part of a survey to search for galaxies with extended radio continuum halos. The results (Sorathia 1994) show the galaxy to have extended radio continuum emission to distances as far as 8 kpc from the midplane (see §3.5). Since this galaxy is also infrared bright (Soifer *et al.* 1987, see also §3.6), it therefore appeared to be a good candidate for finding high-latitude neutral hydrogen arcs and filaments. Throughout this thesis, we use a distance to NGC 3044 of 21.5 Mpc (see §3.3.4). At this distance, 1'' $\equiv$ 0.10 kpc.

In this chapter, we present the neutral hydrogen, carbon monoxide, radio continuum, infrared and H α results pertaining to this galaxy in §3.3, §3.4, §3.5, §3.6 and §3.7, respectively. In §3.8, we show the correlations of the various ISM components in NGC 3044, drawing results from all the wavelength bands described before this section and in §3.9, a summary of the chapter is given.

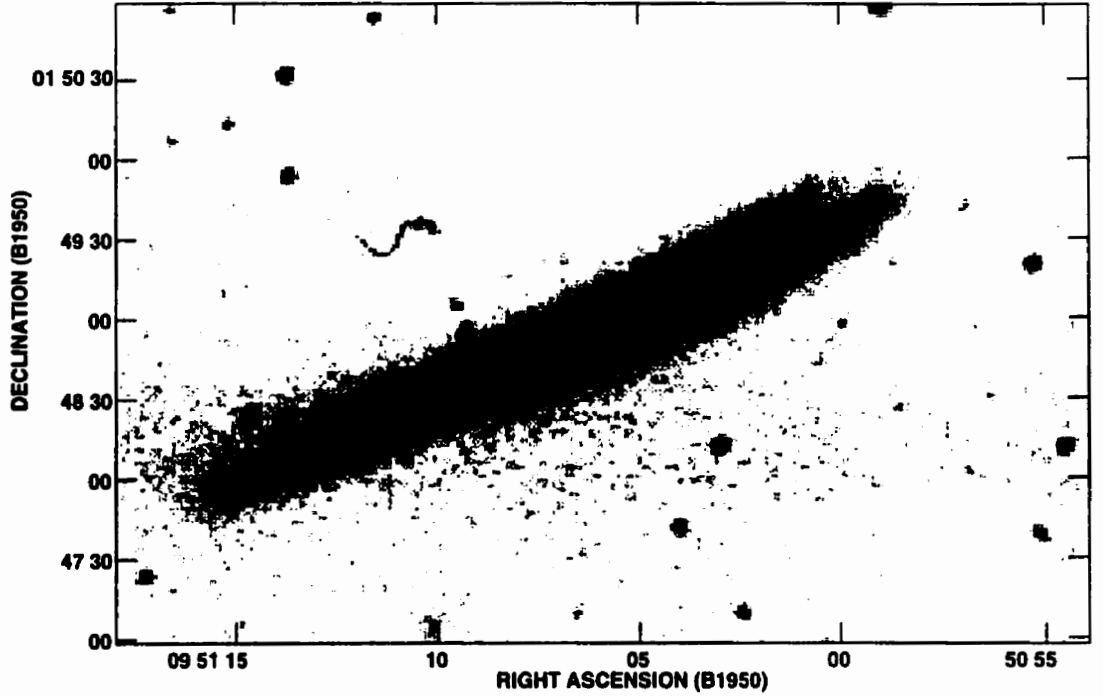


Figure 3.1: Optical image of NGC 3044

3.2 Observations

A detail description of the observations and data reduction procedures are presented in Chapter 2. Here we recapitulate them for the sake of completeness. We have obtained the 21 cm neutral hydrogen (HI) data at the VLA in the C-configuration. The data was “cleaned” using natural and uniform weighting to give rise to two data cubes. The natural weighting cube has higher sensitivity while the uniform weighting cube has higher resolution. The HI observing parameters are listed in Table 2.1.

The carbon monoxide (CO) data was obtained at the JCMT. Three rotational transitions, ^{12}CO $J=2\rightarrow1$, ^{13}CO $J=2\rightarrow1$ and ^{12}CO $J=3\rightarrow2$ were observed mainly within a few kpc of the galaxy’s nucleus. In the ^{12}CO $J=2\rightarrow1$ transition, positions out to about 10 kpc are also obtained along the major axis of the galaxy. In order to

compute the $^{12}\text{CO } J=2 \rightarrow 1$ to $^{12}\text{CO } J=1 \rightarrow 0$ line ratio, we make use of the published $^{12}\text{CO } J=1 \rightarrow 0$ integrated intensity of Solomon and Sage (1988) at the centre of the galaxy, with appropriate scaling to the main beam temperature scale. As the telescope beam for the different transitions are different (45'' for $^{12}\text{CO } J=1 \rightarrow 0$ 21'' for $^{12}\text{CO } J=2 \rightarrow 1$ and $^{13}\text{CO } J=2 \rightarrow 1$ and 14'' for $^{12}\text{CO } J=3 \rightarrow 2$), we were careful to fully sample the area of the larger beam by observing with the smaller beam in steps of half beamwidths. This way, we are able to compare the $^{12}\text{CO } J=2 \rightarrow 1$ to $^{12}\text{CO } J=1 \rightarrow 0$ and the $^{12}\text{CO } J=3 \rightarrow 2$ to $^{12}\text{CO } J=2 \rightarrow 1$ line ratios. For the observed positions and integration time, see Table 2.3.

The radio continuum data was adopted from the published data of Sorathia (1994). Beam sizes and rms map noise are listed in Table 2.5. The high-resolution IRAS (HIRES) maps were obtained from IPAC, beam sizes and rms map noise are listed in Table 2.6. Finally, an $\text{H}\alpha$ image was obtained from the Capilla Peak Observatory 0.6m telescope. The image is continuum-subtracted but not flux-calibrated.

3.3 The HI Distribution in NGC 3044

3.3.1 The HI Channel Maps

The result of a radio interferometric observation is a three-dimensional data cube with right ascension, declination and velocity as the axes. The distribution of neutral hydrogen in velocity space can most easily be discerned from velocity channel maps. The naturally weighted (see Appendix A) channel maps in Figure 3.2 show clearly that the SE side of the galaxy is receding and the NW side is approaching. Since the dust lane occurs most prominently along the southern edge of the galaxy in Figure 3.1, this must be the closest edge to us. Therefore, any trailing spiral structure observed

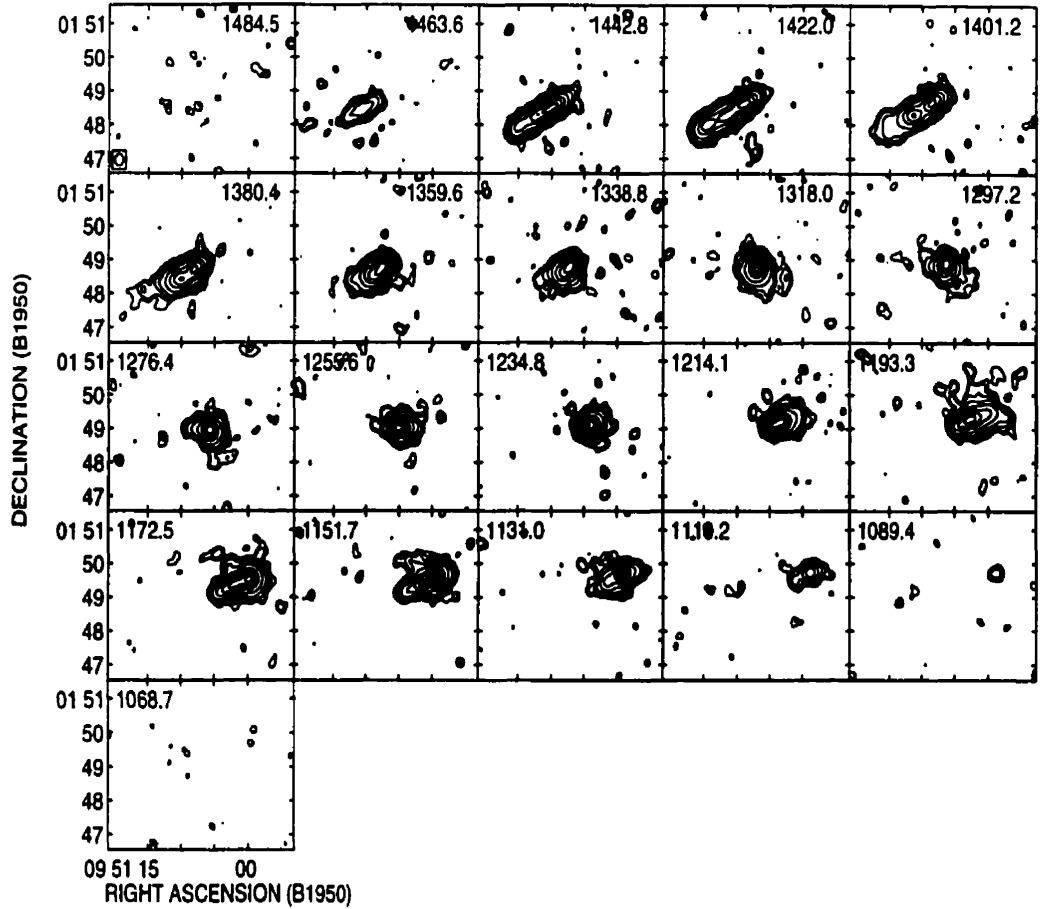


Figure 3.2: Naturally weighted velocity channel maps of NGC 3044. Contour levels are at $1.0(1.5\sigma)$, 1.3, 1.9, 3.2, 6.4, 12.8, 19.2, 25.6, 32.0, 38.4, 44.8 mJy/beam. The channel width is 20 km s^{-1} centred at the velocity which appears at the upper left or right corner of each frame. The synthesized beam is shown at the lower left corner of the first frame.

should have an inverted “s” shape.

There is distinct evidence of HI arcs and extensions and high latitude features away from the plane of the galaxy. For example, on the SE side, a disconnected feature at $\alpha = 9^{\text{h}}51^{\text{m}}7^{\text{s}}.7$, $\delta = 1^{\circ}47'21''.0$ reaches a height of 11.2 kpc in the 1422 km s^{-1} channel and an impressive high-latitude extension is found on the NW side at $\alpha = 9^{\text{h}}51^{\text{m}}3^{\text{s}}.3$,

$\delta = 1^{\circ}50'0''$ from 1110 km s^{-1} to 1235 km s^{-1} . It reaches a projected height of 9.5 kpc from the midplane. These features and others will be discussed in more detail in Chapter 5.

The channel maps also reveal the asymmetric distribution of gas in the galaxy, which we highlight in Figure 3.3, by superimposing selected channel maps of equally red- and blue-shifted velocities with respect to systemic. The HI distribution of the receding side (solid contours) is much more elongated than that of the approaching side (dotted contours) and the approaching side is more “active” displaying the largest high-latitude extensions above the HI disk. The disk appears to be fairly straight at high velocities, although the outer contours ($1.5 - 3\sigma$) on the NW side dip below the major axis, probably due to an extension (feature 12, see Chapter 5). The asymmetry is discussed in §6.1.1.

3.3.2 The Column Density Maps

The column density map is obtained, from the zeroth moment of the velocity profile,

$$N_{HI}(\alpha, \delta) \propto \Delta v \sum_{i=1}^{n_{tot}} I_i(\alpha, \delta), \quad (3.1)$$

where $I_i(\alpha, \delta)$ is the surface brightness at velocity v_i , Δv is the channel spacing and n_{tot} is the number of velocity channels (van Gorkom and Ekers 1994). This relation comes from

$$N_{HI} = 1.823 \times 10^{18} \int T_B dv \text{ cm}^{-2}, \quad (3.2)$$

where T_B is the brightness temperature, and the Rayleigh-Jeans formula

$$T_B = \frac{c^2 I_\nu}{2k\nu^2}, \quad (3.3)$$

where c is the speed of light and I_ν is the specific intensity at the observed frequency ν , under the assumption of optical thinness (see §3.3.4). In Figure 3.4, the column

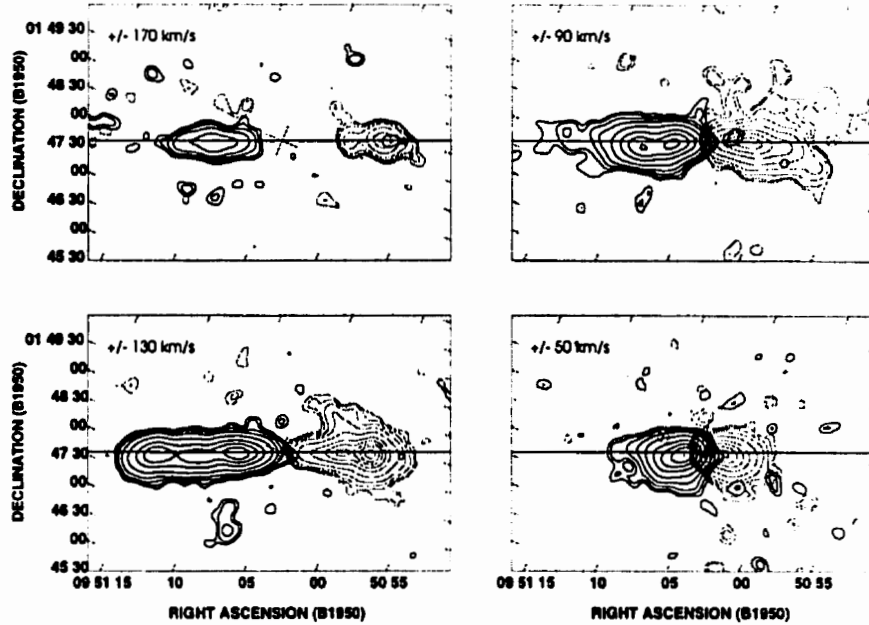


Figure 3.3: Selected velocity channels showing the asymmetric distribution of gas in NGC 3044

Channels symmetrical with respect to the systemic velocity are superimposed. The rotation curve peaks at 150 km s^{-1} (Table 3.3). Solid contours are positive in velocity and dotted contours are negative. The cross represents the kinematic centre and the major axis is shown as the horizontal line across. Contours are as in Fig 3.2. Note that the images have been rotated so that the major axis appears horizontal.

density map of NGC 3044 for the uniformly weighted data is superimposed on the optical grey-scale image from the Digitized Sky Survey. The naturally weighted column density map (contours and grey-scale) is shown in Figure 3.5. In Figure 3.4, one extension is particularly obvious – labelled F10 (feature 10, see Chapter 5). The disk’s column density peaks at $\alpha = 9^h51^m7.7$, $\delta = 1^\circ48'48''.1$. Besides this peak, there are three other peaks along the major axis. The two outermost ones are roughly symmetrically located with respect to the central peak, both at a distance of about 13 kpc (130'') on either side. The NW peak is 2.5 times stronger in intensity than its counterpart on the SE side, being $8.5 \times 10^{21} \text{ cm}^{-2}$ and $3.3 \times 10^{21} \text{ cm}^{-2}$, respectively. The peak of the HI distribution does not coincide with the peak of the optical image but is offset by about 43'' along the major axis to the SE. The optical distribution extends to the outer SE HI peak, but with very low intensity. Interestingly, there is another HI column density enhancement ($N_{HI} = 7.6 \times 10^{21} \text{ cm}^{-2}$) between the central peak and the outer NW peak, directly below feature 10. This smaller peak seems to coincide with a region of low surface brightness on the optical image, which could be due to absorption by a dust lane.

Measured from the outermost contour of the naturally weighted map (Fig. 3.5), the HI disk spans a length of 5'.7 or $2.3 \times R_{25}$ along the major axis, where R_{25} is the optical radius of the galaxy at the 25th magnitude level. Feature 10 is clearly visible and more extended than in Figure 3.4 along with various other extensions. F10 extends out to about 8 kpc above the plane of the galaxy in Figure 3.5. In fact, an extensive disturbance in the region near feature 10 can be seen in this figure. We show in Chapter 5 that feature 10 is an expanding supershell. Other protruding features are also visible in Figure 3.5. For example, the hole at $\alpha = 9^h51^m4.0$, $\delta = 1^\circ48'10''$ and numerous protrusions along the northern edge of the galaxy can be seen.

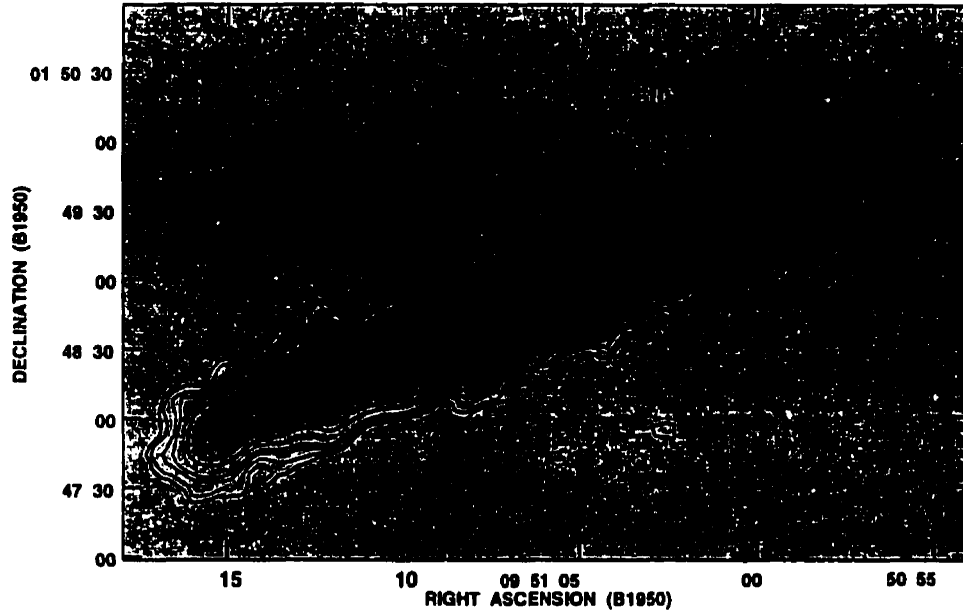


Figure 3.4: The uniform weighting column density map of NGC 3044. The map is superimposed on the optical Digital Sky-Survey image (Fig. 3.1). Hanning smoothing is applied in velocity space using 3 channels and spatially using a Gaussian of $\text{FWHM}=20''$. A cutoff at the 1σ level is applied. Contour levels are at 1.8, 3.0, 4.8, 6.0, 12.0, 30.1, 48.1, 60.0, 72.2, 90.2, 108.3, $120.3 \times 10^{20} \text{ cm}^{-2}$. Feature 10 is labelled as F10.

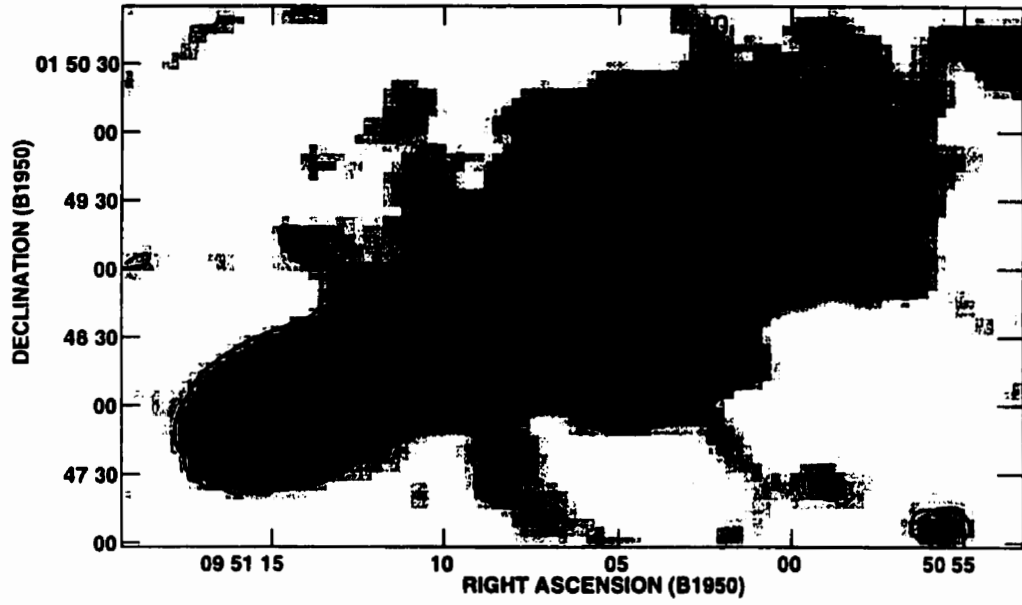


Figure 3.5: The natural weighting column density map of NGC 3044. The column density contours are superimposed on grey-scale map. Contour levels are at $1.6, 2.6, 3.2, 4.0, 5.3, 13.2, 26.4, 39.7, 52.9, 66.1, 79.3, 92.5, 97.8 \times 10^{20} \text{ cm}^{-2}$.

3.3.3 The Velocity Field

The intensity weighted mean velocity is obtained from the first moment analysis,

$$\bar{v} = \frac{\sum_{i=1}^{n_{tot}} I_i(\alpha, \delta) v_i}{\sum_{i=1}^{n_{tot}} I_i(\alpha, \delta)} \quad (3.4)$$

(van Gorkom and Ekers 1994). The naturally weighted velocity field of NGC 3044 is shown in Figure 3.6. The kinematic major axis is obtained by eye and passes through the points of steepest gradient of most inner (closest to the galaxy's centre) isovelocity contours. The kinematic minor axis is along the inner part of the contour at the systemic velocity as obtained from the global profile (see next subsection). The kinematic centre is then the intersection of the major and minor axes. The kinematic major axis is parallel to the optical major axis to within one degree out to a radius of about $50''$ (5 kpc). The kinematic minor axis is not perpendicular to the inner kinematic major axis, this is typically an indication of a bar structure (Bosma, 1981), which is consistent with the optical classification of this galaxy. Beyond about $1'.7$ (10 kpc) on the NW side, the velocity field becomes disturbed. For example, there is a closed 1160 km s^{-1} contour at the position of F10. On both sides, beyond about $50''$ (5 kpc), the kinematic major axis bends slightly towards the south. Therefore the major axis does not resemble the more commonly seen kinematic warps in other edge-on galaxies, which looks like an integral sign or the inverse of one. Hence, we interpret the disturbance near feature 10 as high-latitude features instead of a simple warp.

In Figure 3.6, the kinematic centre of the galaxy is represented by $\bigcirc$ ($\alpha = 9^h 51^m 53.9$, $\delta = 1^\circ 48' 58''.7$). This position is significantly different from the position of both the column density peak (labelled $\diamond$ in Fig. 3.6) as well as the optical centre (labelled $+$), so that the kinematic centre is between the column density peak and

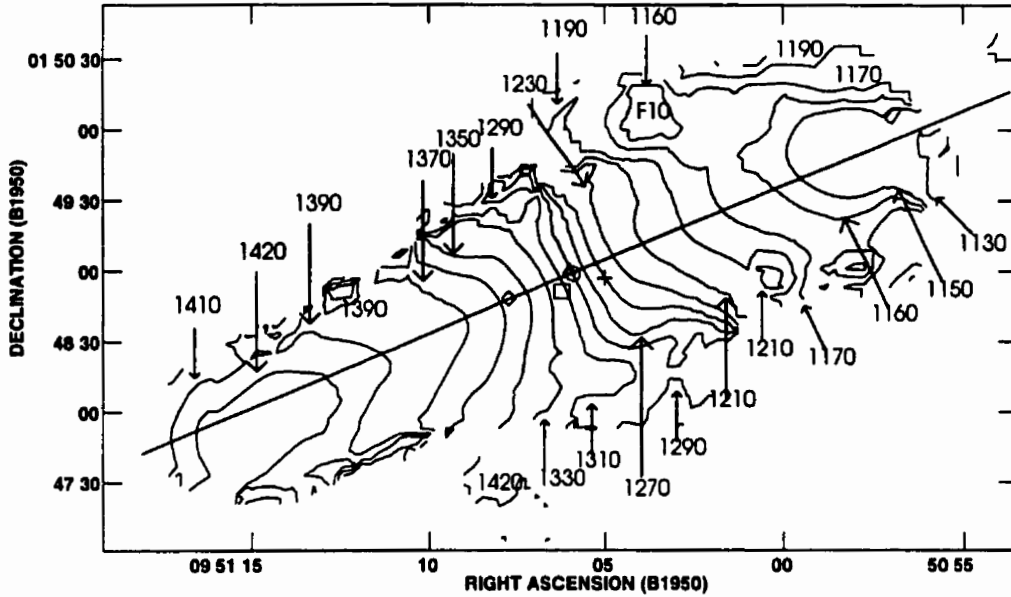


Figure 3.6: The naturally weighted velocity field of NGC 3044. Contours are 20 km s^{-1} apart starting from 1130 km s^{-1} to 1410 km s^{-1} . Also included are contours of 1160 and 1420 km s^{-1} . The kinematic major axis is indicated by the straight line across. Symbols represent the different peaks and centres described in the text. + is the optical centre, $\triangle$ is the radio continuum peak, $\diamond$ is the column density peak, $\bigcirc$ is the kinematic centre and $\square$ is the model centre.

optical centre. However, the kinematic centre does coincide with the peak of the radio continuum map (represented by $\triangle$). The kinematic centre given by our model (labelled $\square$) is also shown. This will be discussed more fully in §3.3.5. Here, we identify the radio continuum centre as the ‘true’ centre of the galaxy because it does not suffer from any dust absorption and because it coincides with the kinematic centre.

Notice all velocity contours have bends and kinks in them, especially near the outer edges of the contours. Such features are usually explained by shock fronts occurring at the inside edge of spiral arms as a density-wave perturbs the local velocity field (Visser 1980). However, due to the high inclination of NGC 3044, this is difficult to verify from the column density map. At the location of feature 10, the velocity field is inconsistent with normal galactic rotation; instead it is more blueshifted. If feature 10 is actually located at a larger distance (so that its distance from the nucleus in Figure 3.6 is just a foreshortened distance in projection), then we would expect its radial velocity to be redshifted. It is clear that feature 10 does not follow the general flow of material in the disk below it.

3.3.4 The HI Global Profile

The global properties of a spiral galaxy, e.g., systemic velocity, distance and HI mass, can be determined from the global profile (i.e., total flux density as a function of radial velocity). Figure 3.7 shows the global profile of NGC 3044 from the naturally weighted data. This is obtained by summing all the real emission (judging by eye) in each velocity channel. The profile consists of the double-horned feature typical of a normal, unresolved, spiral galaxy. Our line shape compares very well with previously published data (Staveley-Smith and Davies 1988, 12' beam).

The global properties of NGC 3044 are tabulated in Table 3.2. Row 1 gives the

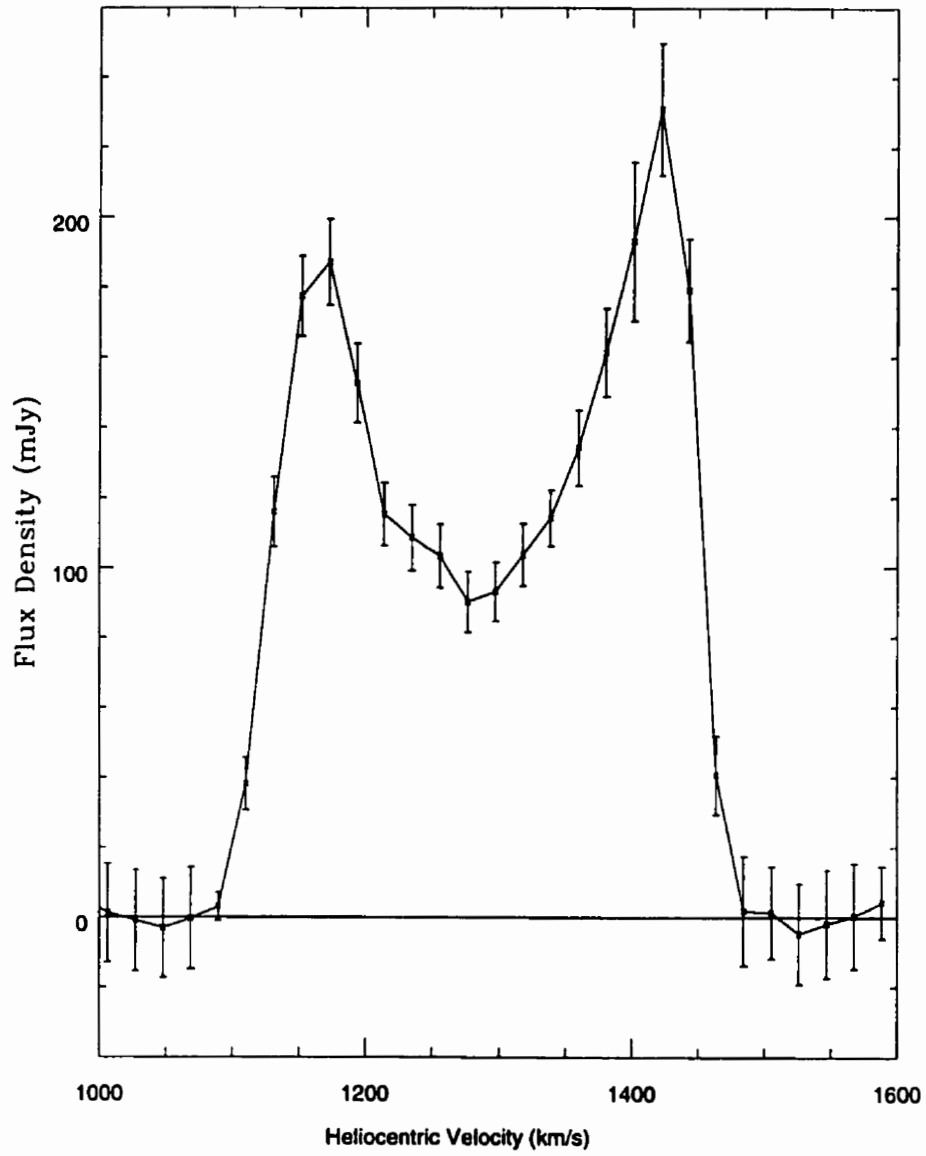


Figure 3.7: The naturally weighted global profile for NGC 3044. Error bars are at the 1σ level.

systemic velocity of the galaxy. This is the velocity at the centre of the 20% level of the peak intensity (mean of the two asymmetric peaks). Row 2 gives the distance which is deduced from the systemic velocity with respect to the Local Standard of Rest (LSR)³ and corrected to the reference frame of the 3K background radiation⁴ [using equation (82) in the RC3]. The distance of this galaxy derived from the Tully-Fisher relation is given in Bottinelli *et al.* (1984) as 17.7 ± 1.7 Mpc. Considering the uncertainty in the value of the Hubble constant used in deriving the distance in Table 3.2 (25%), the discrepancy is insignificant. Row 3 gives the velocity width at the 20% level and is not corrected for inclination due to the high inclination for this galaxy [$i = 84^\circ \pm 2^\circ$, Bottinelli *et al.* (1984)]. An inclination correction would increase this value by less than 1%.

The integrated flux density of NGC 3044 is given in row 4. The value is obtained by integrating the global profile from 1068 km s^{-1} to 1484 km s^{-1} . Our value agrees with both Staveley-Smith and Davies (1988) and Krumm and Salpeter (1980). Row 5 shows the estimated HI mass of the galaxy using the equation $M_{HI} = 2.35 \times 10^5 D^2 \int S \cdot dV$ where M_{HI} is in $M_\odot$, D is in Mpc and $\int S \cdot dV$ is in $\text{Jy} \cdot \text{km s}^{-1}$. This equation is valid under the assumption of optical thinness (as is the equation for column density, equation 3.2). Haynes and Giovanelli (1984) investigated the effect of HI self-absorption on HI integrated flux as a function of morphological type and galaxy inclination. They concluded that for Sc-type galaxies with inclinations such as that for NGC 3044, the correction factor is about 1.3. Thus M_{HI} could be up to 30% higher than the value in Table 3.2.

³The Local Standard of Rest is the reference frame, centred on the sun, that moves in a circular motion around the Galactic centre so that the nearby stars are at rest.

⁴The 3K background radiation is the relic radiation of the Big Bang that has been redshifted due to the expansion of the universe.

Table 3.2: Global HI Properties of NGC 3044

Row	Parameter	NGC 3044
(1)	V_{sys}	$1287 \pm 10 \text{ km s}^{-1}$
(2)	D	21.5 Mpc
(3)	$\Delta V_{20\%}$	$351 \pm 10 \text{ km s}^{-1}$
(4)	$\int S \cdot dV$	$48.2 \pm 3.6 \text{ Jy} \cdot \text{km s}^{-1}$
(5)	M_{HI}	$(5.3 \pm 0.4) \times 10^9 M_{\odot}$
(6)	M_{HI}/L_B^a	$0.22 \pm 0.02 M_{\odot}/L_{\odot}$
(7)	M_T^b	$(1.5 \pm 0.1) \times 10^{11} M_{\odot}$
(8)	M_T/L_B	$6.1 \pm 0.3 M_{\odot}/L_{\odot}$
(9)	M_{HI}/M_T	0.036 ± 0.003

^a L_B is calculated using the total “face-on” apparent blue magnitude (B_o^T) given in the RC3 and using a value of +5.48 for the absolute blue magnitude of the Sun.

^bRadius is taken to be the maximum extent of the third contour in the naturally weighted position-velocity diagram (Fig. 3.8) and V_{rot} is the average of the maximum blue- and red-shifted velocities with respect to the systemic velocity measured using the same contour. The third (4.5σ) contour is used so as to avoid the protruding feature on the approaching side of the p-v diagram (see Fig. 3.8) which probably does not reflect the maximum blueshifted rotational velocity.

As a check of optical thinness, we estimate the mean optical depth by

$$\tau = -\ln(1 - T_B/\langle T_S \rangle) \quad (3.5)$$

where T_B is the observed HI brightness temperature and $\langle T_S \rangle$ is the opacity weighted mean spin temperature along the line of sight. The value of $\langle T_S \rangle$ is unknown, but based on the values found by Dickey and Brinks (1988) for M31, we can obtain some feel of what the optical depth of NGC 3044 may be. The range of $\langle T_S \rangle$ obtained by Dickey and Brinks varies from >160 K to >460 K with a mean of about 300 K. As NGC 3044 is infrared bright and M31 is not (Soifer *et al.* 1987), it is reasonable to assume that the mean spin temperature in NGC 3044 will be higher than that of M 31. The peak brightness temperature for NGC 3044 is 83.1 K in the 13'' beam, thus $\tau_{max} = 0.20$ if $\langle T_S \rangle = 460$ K and $\tau_{max} = 0.73$ if $\langle T_S \rangle = 160$ K. Under these assumptions, we conclude that optical depth effects should not be strong ($\tau < 1$). If T_S is higher, then $\tau \ll 1$. We have also obtained the HI masses of the approaching and receding sides separately and find the receding side is 14% more massive than the approaching side while the uncertainty due to the error bars in the global profile is only 8%.

Row 6 in Table 3.2 gives the HI mass to blue luminosity ratio. Row 7 gives the estimated total mass of the galaxy within the outermost detectable HI radius. The usual equation assuming a spherical geometry is used

$$M_T = 2.33 \times 10^5 R V_{rot}^2 (M_\odot), \quad (3.6)$$

where R is taken to be the maximum extent (15.3 kpc) of the third contour (4.5σ) in the naturally weighted position-velocity (p-v) diagram (Fig. 3.8) and V_{rot} is the average of the maximum blue- and red-shifted velocities with respect to the systemic

velocity measured using the same contour (199 km s^{-1}). The 4.5σ contour is used so as to avoid the protruding feature on the approaching side of the p-v diagram (see Fig. 3.8) which probably does not reflect the maximum blueshifted rotational velocity. The quoted uncertainty reflects only the asymmetry of the receding and the approaching sides of the galaxy, which dominates the errors. Using a spherical geometry may result in an overestimate of the true total mass within R if the total mass is dominated by the disk component. However, this overestimation will be less than 40% (Lequeux 1983). Row 8 gives the ratio of total mass to blue luminosity and row 9 gives the fractional HI mass.

The values of Table 3.2 were compared with those of Roberts and Haynes (1994) (RH hereafter), correcting to their value of $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$. We find that M_{HI} , M_T/L_B and M_{HI}/M_T all fall within the ranges of the corresponding parameters under their Sbc-Sc group. M_T as calculated above does not lie within the range given in RH, but when we re-computed M_T using the width of our global profile at the 20% level (to be consistent with the method used in RH), we obtain a value of $M_T = (17 \pm 3) \times 10^{10} M_\odot$. This value then agrees with RH. The difference in M_T obtained using the two methods lies in the difference in V_{rot} . Since the higher M_T listed in Table 3.2 is obtained from the major axis slice, it should be the better estimate of the galaxy's total dynamical mass.

To better constrain the geometrical parameters as well as to find the density distributions and velocity profile of NGC 3044, we apply a simple modeling routine as described below.

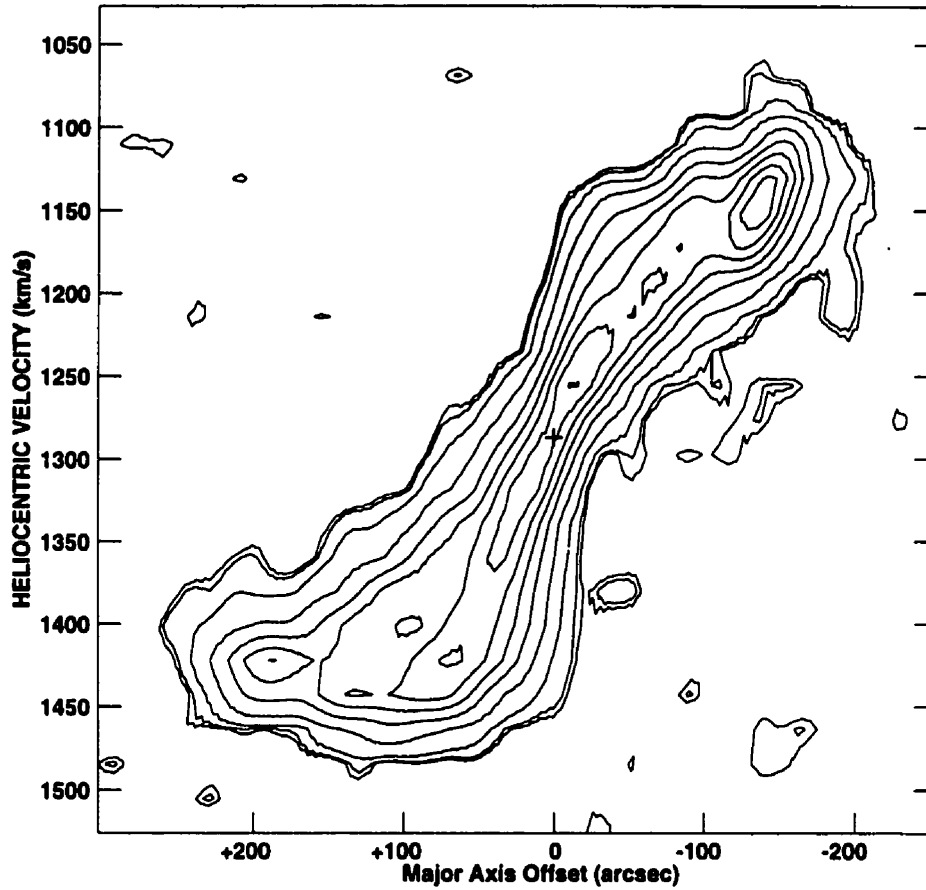


Figure 3.8: Position-velocity diagram along the kinematic major axis of NGC 3044. The data cube used is naturally weighted. Contour levels are 0.8(1.8σ), 1, 2, 5, 10, 15, 20, 25, 30, 35, 40 mJy/beam. The cross indicates the kinematic centre.

3.3.5 Data Cube Modeling and Results

The methods used in §3.3.2 and §3.3.3 can serve only as a preliminary analysis of the spatial and velocity distribution of an edge-on galaxy because the flux density at each pixel is an integration along the line of sight which spans many galactocentric radii. Thus the intensity-weighted mean velocity (Figure 3.6) is not a good description of the galaxy's velocity field except as an indicator of distortions and as a locator of the major and minor axes. The actual magnitudes of the velocity contours will not be meaningful. In addition, the usual method of obtaining a galaxy's velocity dispersion is to perform the second moment analysis of the velocity profile. Thus the dispersion will not be a measure of the true dispersion of the clouds as much as a measure of different radial velocities over different galactocentric radii. Other methods therefore need to be applied in order to find the spatial and velocity distributions of an edge-on galaxy.

To make use of all available data, we instead use the technique of Irwin and Seaquist (1991) and Irwin (1994) which models the intensity at every pixel given the radial and perpendicular density distributions and the form of the rotation curve. The routine, CUBIT, interfaces with AIPS and makes use of the Levenberg-Marquardt algorithm for the non-linear least squares fitting. CUBIT assumes optical thinness along any line-of-sight and calculates the intensity at every pixel according to the radial and perpendicular (to the plane of the galaxy, also called the z-axis) density distributions and the form of the rotation curve selected by the user. The free parameters are some subset of: RA and DEC of the nucleus, major axis position angle (PA), inclination of the galaxy (i), the systemic velocity (V_{sys}), the galactocentric radius, R_{max} , at which maximum rotational velocity, V_{max} occurs, the Brandt rotation curve

(Brandt and Scheer 1965) index (m), the peak volume density of the distribution (n_{max}), the radial density scale lengths (r_o and r_i , see below), and the scale height of the vertical distribution (z_o). In addition, a ringed density distribution centred at radius R_o is also possible (see below). The calculated model intensities per pixel are then smoothed to the spatial resolution of the data and the residual (data minus model) are found. The routine adjusts the trial input parameters until the model producing the lowest residuals is found.

The trial density distributions are exponential or Gaussian. For the exponential distribution, we have

$$n(r, 0) = n_{max} e^{-r/r_o} \text{ (cm}^{-3}\text{)} \quad \text{radially and} \quad (3.7)$$

$$n(r, z) = n(r, 0) e^{-z/z_o} \text{ (cm}^{-3}\text{)} \quad \text{vertically,} \quad (3.8)$$

where $n(r, 0)$ is the midplane volume density at galactocentric radius r and z is the height above the plane. For the Gaussian distribution, we have

$$n(r, 0) = n_{max} e^{-r^2/r_o^2} \text{ (cm}^{-3}\text{)} \quad \text{radially and} \quad (3.9)$$

$$n(r, z) = n(r, 0) e^{-z^2/z_o^2} \text{ (cm}^{-3}\text{)} \quad \text{vertically.} \quad (3.10)$$

In addition, a Gaussian or exponential *ring* distribution in the plane of the galaxy centered at radius R_o is also possible. That is, for a Gaussian ring distribution,

$$n(r, 0) = n_{max} e^{-r^2/r_o^2} \text{ (cm}^{-3}\text{)} \quad \text{for } r \geq r_o \quad (3.11)$$

$$n(r, 0) = n_{max} e^{-r^2/r_i^2} \text{ (cm}^{-3}\text{)} \quad \text{for } r < r_o \quad (3.12)$$

where r_o and r_i are the outer and inner scale lengths, respectively.

The choices for the form of the velocity curve are the Brandt curve, given by

$$V(r) = V_{sys} \pm \frac{(r/R_{max})V_{max}}{[\frac{1}{3} + \frac{2}{3}(r/R_{max})^m]^{\frac{3}{2m}}} \text{ (km s}^{-1}\text{)} \quad (3.13)$$

or a user-specified numerical rotation curve which we take from the velocity-position diagram along the major axis (Fig 3.8) (allowing the amplitude to vary). The model also allows for a velocity dispersion (σ_v). Using this routine, the geometrical parameters (particularly the inclination which cannot normally be found without an assumption of the scale height), the velocity distribution and the density distribution (radial and vertical) are extracted using all available data points. For NGC 3044, we model the uniformly weighted data cube as it has a higher spatial resolution than the naturally weighted cube, yet the integrated flux density (42 ± 6 Jy km/s) still agrees with that of the naturally weighted cube (see Table 3.2). There are 2248 independent data points of real positive emission, hence the free parameters should be well constrained.

The best fit results are shown in Table 3.3 for the entire galaxy (column 2), the receding (column 3) and advancing (column 4) sides. Column 1 is a list of free parameters. Brandt rotation curves are used for all the models in this table, since they resulted in better fits in all trials than a user-specified numerical curve. We shall hereafter use notations such as ‘RG(GS)-EX’ to represent a model having a Gaussian ring distribution in the plane and an exponential distribution in the z-direction. The uncertainties quoted are either standard deviations of the results of all trial models (including those not shown in Table 3.3) or formal 1σ errors from the fit of the best model, whichever is larger. The following subsections discuss the model results.

Galaxy’s Geometry

The modeled kinematic centre is well constrained amongst the different models (including those not shown here) giving a standard deviation of $0''.07$ in RA and $0''.4$ in DEC. As mentioned before, the column density peak is shifted towards the SE

Table 3.3: Model Parameters for NGC 3044

Model Parameter (1)	Whole Galaxy RG(GS)-GS (2)	Receding Side GS-GS (3)	Approaching Side RG(GS)-EX (4)
$\alpha_o(1950)$	$9^h51^m6^s.15 \pm 0^s.07$	...	...
$\delta_o(1950)$	$1^\circ48'51''.2 \pm 0''.4$	...	...
PA($^\circ$)	112.95 ± 0.10	113.45 ± 0.04	111.4 ± 0.3
$i(^\circ)$	84.9 ± 0.4	85.3 ± 0.3	86.1 ± 0.2
$V_{sys}(\text{km s}^{-1})$	1298 ± 4	...	...
$V_{max}(\text{km s}^{-1})$	150 ± 3	149 ± 2	151 ± 3
$R_{max}(kpc)$	8.5 ± 0.5	6.5 ± 0.3	12 ± 5
$R_o(kpc)$	3.1	...	10.9
m	0.99 ± 0.18	0.64 ± 0.15	0.48 ± 0.26
$n_{max}(\text{cm}^{-3})$	0.29 ± 0.11	0.30 ± 0.14	0.25 ± 0.12
$r_o(kpc)$	7.1 ± 0.9	8.5 ± 1.1	2.5 ± 0.3
$z_o(kpc)$	0.56 ± 0.05	0.65 ± 0.05	0.60 ± 0.04
$r_i(kpc)$	1.60 ± 0.03	...	3600 ± 39
$\sigma_v(\text{km s}^{-1})$	24.3 ± 2.2	19.9 ± 2.2	17.7 ± 2.2

(receding) side of the galaxy (*cf.* §3.3.3). As part of the modeling process, we forced the model centre to coincide with the column density peak and the radio continuum peak separately. These resulted in worse models for all combinations of density distributions implying real offsets of these peaks from the model's centre. The modeled kinematic centre is $2''.3$ east and $8''.8$ south of the radio continuum peak ($9^h51^m6^s.0$, $1^\circ49'0''.0$, see Fig. 3.3.3). As the receding side is more massive, it is natural that the model centre is being weighted towards this side, hence the offset from the radio continuum centre. The peak of the column density map is located at $\alpha = 9^h51^m7^s.7$, $\delta = 1^\circ48'48''.1$, this is $23''.3$ east and $3''.1$ south of the modeled centre. The differences in the peak positions are significant. The major axis p-v diagram (Fig. 3.8) also shows an asymmetry in the sense that the receding side of the galaxy extends further. In addition, the flat part of the rotation curve shows up more prominently on this side. It therefore appears that either the galaxy's HI emission has been 'truncated' on the approaching side or the receding side emission has been 'stretched out'. We feel that the former is probably true as the receding side of the p-v diagram more closely resembles the p-v diagrams of other giant spirals, and also because the approaching side is disturbed (§3.3.1).

The position angle and inclination of the galaxy are also well determined. Various models resulted in standard deviations of $0^\circ.10$ and $0^\circ.4$ for these two parameters, respectively. The position angle agrees with that given in the RC3 (note that there is a mistake in the RC3, the position angle listed should be 113° instead of 13°). The inclination from the model ($84^\circ.9$) agrees with Bottinelli *et al.* (1984) and Staveley-Smith and Davies (1988) who obtain $i=84\pm2^\circ$ and $90\pm13^\circ$ respectively. The former assumes an intrinsic oblateness of 0.15 while the latter uses 0.20. Our value is independent of the intrinsic axial ratio, and should be an improvement over the previous

estimates.

The Velocity Field

The modeled systemic velocity agrees with that measured from the global profile of the data (see Table 3.2) to within errors. The rotation curve parameters, V_{max} and R_{max} , are also well-defined, with the spread in V_{max} within 10% of the velocity resolution while the spread in R_{max} is determined to 40% of the HPBW. The shape of the rotation curve is determined by the Brandt index, m , and the spread in this parameter is 18% amongst all trials. When a velocity dispersion is included in the models, results for every model improved significantly. For the best model, the optimum FWHM of the Gaussian smoothing function is 57.2 km s^{-1} (2.75 channels) corresponding to a velocity dispersion of 24.3 km s^{-1} . This value reflects all non-circular motions along each line of sight, including any velocity variations due to spiral arms, and is a global average. Note however that it does correct for the fact that different rotational velocities are probed along a single line of sight due to a variation in galactocentric radius (*cf.* beginning of this subsection). This velocity dispersion is comparable to that found in NGC 5775 (Irwin, 1994) and is about 3 times the velocity dispersion found for the Milky Way galaxy, which only measures the rms cloud velocity (Spitzer, 1978).

The Density Distributions

The model parameters related to the density distributions vary significantly amongst different models. Some of the variation is expected since the parameters are defined differently between some of the models. While there is no obvious central hole in the

column density map (Fig. 3.4), the best model found is a ring distribution [RG(GS)-GS] rather than a distribution which peaks at the centre. The volume density at the radius of the ring (3.1 kpc) is 0.29 cm^{-3} . This is very similar to the average midplane density of our Galaxy between 4 to 8 kpc which is $\approx 0.35 \text{ cm}^{-3}$ (Burton and Gordon 1978). The outer radial scale length is 7.1 kpc, or 20% of the length of the HI disk as measured on the outermost contour of the column density map (Fig. 3.4). As a comparison, the Galactic HI density stays roughly flat from about 4 to 10 kpc and falls off beyond that. The inner scale length is the least constrained, its value depends sensitively on the position of the ring. The uncertainty associated with this parameter in Table 4 is therefore taken to be the formal $1\text{-}\sigma$ uncertainty of the fit instead of the standard deviation from the variation between the different models. Our best model gives the inner scale length of 1.60 kpc, about half the radius of the ring.

The vertical scale height given by the best model is 0.56 kpc. This value is obtained as a global parameter, an averaged over the entire disk of the galaxy. Note that in specific places, e.g., feature 10, the HI extends to 8 kpc in projection. In the Galaxy, it is known that the HI distribution between 4 to 8 kpc consists of two components, a central layer with a FWHM of ≈ 0.1 kpc, and a low-intensity, higher temperature component with a FWHM of ≈ 0.5 kpc (Lockman, 1984). It is perhaps more helpful to compare the vertical scale height with an external galaxy. NGC 891 is also an edge-on, IR-bright spiral which exhibits high-latitude HI features. van der Kruit (1981) modeled the thickness of its HI layer and found that the FWHM of the z -distribution increases with galactocentric radii. The FWHM varies from 0.32 kpc at a radius of 4.2 kpc to 1.89 kpc at a radius of 20.8 kpc with an average value of 0.9 kpc. Therefore, NGC 3044 appears to have a moderately thick HI disk compared to the

Galaxy yet not as extensive as that in NGC 891. To check the validity of a thick disk, we modeled the galaxy again by fixing the vertical scale height to a low value (0.1 kpc). This resulted in a significantly worse model fit to the data. In addition, Sorathia (1994) finds a large radio continuum scale height, namely, $\approx 1.8 \pm 0.5$ kpc for the 20 cm C-array data (see §3.5). Thus NGC 3044 has both a moderately thick HI disk as well as a thick radio continuum disk.

Modeling of Receding and Approaching Halves of the Galaxy

As we have noted before, the HI distribution of NGC 3044 is not symmetric in the sense that the HI is more extended on the SE (receding side) and less so on the NW (approaching side). Modeling the receding and approaching side of the galaxy separately enforces this picture. Columns 3 and 4 of Table 3.3 list the best fit parameters for the two halves of the galaxy in comparison with the parameters given by the galaxy as a whole. Column 3 and 4 were obtained by fixing the nucleus position and the systemic velocity given by the best model for the whole galaxy (column 2 of Table 3.3).

The model fits the receding side of the galaxy better which shows that this side of the galaxy is better described by a smooth spatial and velocity distribution of gas. This result simply reiterates what we see in the major axis rotation curve from the data (Fig. 3.8).

Although V_{max} and R_{max} of both sides agree within error, the uncertainty in R_{max} is much larger for the approaching side. The Brandt curve indices show the same trend. The difficulty in pinning down these parameters is due to the fact that on the approaching side, the rotation curve never reaches a terminal velocity. The density distribution parameters for the two halves of the galaxy differ significantly.

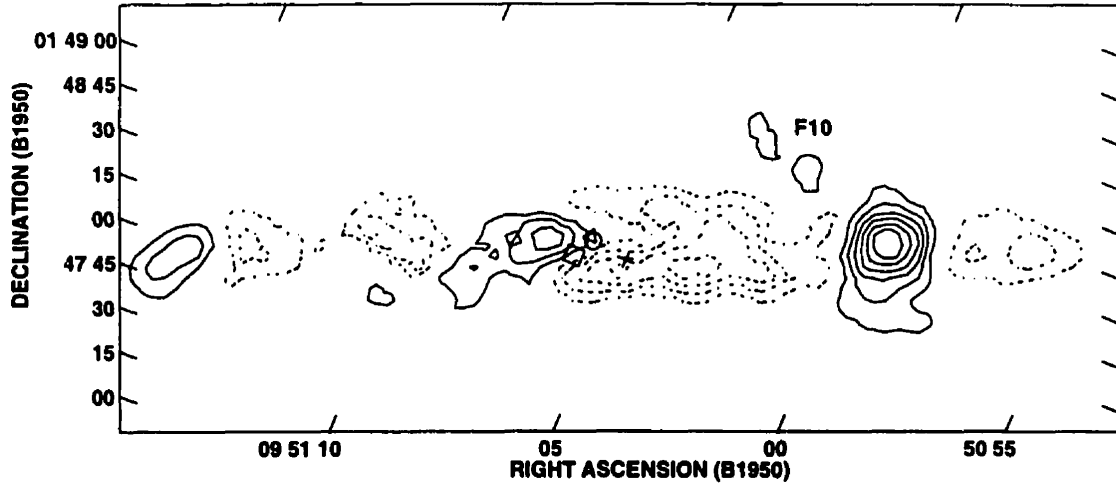


Figure 3.9: Residual column density map

This map is obtained by subtracting model from data. Note that the galaxy in this plot has been rotated so that the major axis appears horizontal. Solid contours represent emission above a smooth distribution (i.e., excess data) and dotted contours represent too much model emission. Contour levels are at 36.1, 30.1, 24.1, 18.1, 12.0, 6.0, -6.0, -12.0, -18.1 and $-24.1 \times 10^{20} \text{ cm}^{-2}$. Feature 10 is labelled as F10 on the map. The symbols have the same meaning as in Figure 3.6.

The receding side is best fitted by a GS-GS distribution while the approaching side prefers a RG(GS)-EX distribution. In the latter case, the location of the ring is at the outer density peak and the inner scale length is extremely high, hence the HI distribution inside this peak is essentially flat. A consequence of the large ring radius is the small outer scale length, as expected. These results for both sides, separately, are consistent with the residual emission observed in Fig. 3.9 (see next section). Finally, the approaching side has a smaller velocity dispersion than the receding side, which can also be seen from the narrower (in velocity) emission on the approaching side in Fig. 3.8.

Comparing Model With Data

Figure 3.9 shows the column density map of the residual cube for the global model result (column 2 of Table 3.3). Negative (dotted) contours represent regions where the amount of gas was over-estimated by the model and positive (solid) contours represent regions of enhanced emission in the galaxy above a smooth density distribution. The peak column density in the residual map is 30% of the peak column density in the data (Fig. 3.4), which shows that the model is able to reproduce 70% of the underlying smooth density distribution of the galaxy at that peak. There remain, however, pixel-to-pixel variations between model and data due to the unevenness of the distribution, as can be seen in Fig. 3.9. For example, feature 10 appears as positive contours, as do the two outer column density peaks (see also Fig. 3.4). The modeled centre does not coincide with the central peak of the zeroth-moment map. As a result, the model under-estimated the column density at the data peak.

In terms of velocity, the model reproduced the velocity field of the galaxy well for the most part. This is confirmed by subtracting the first moment map of the model from that of the data (Fig. 3.10). The rms of this residual velocity field is 16 km s^{-1} , smaller than the velocity resolution of the data (20.8 km s^{-1}). There are regions in the galaxy where the model's velocity cannot reproduce. A good example is the region just under feature 10. In this region, the typical velocity excess is about -50 km s^{-1} (i.e., model over-estimated the velocity) which represents the highest departure of the model from the data. This is consistent with the observation made in §3.3.3, which shows that the velocity field near feature 10 is more blueshifted for its location than expected from normal galactic rotation.

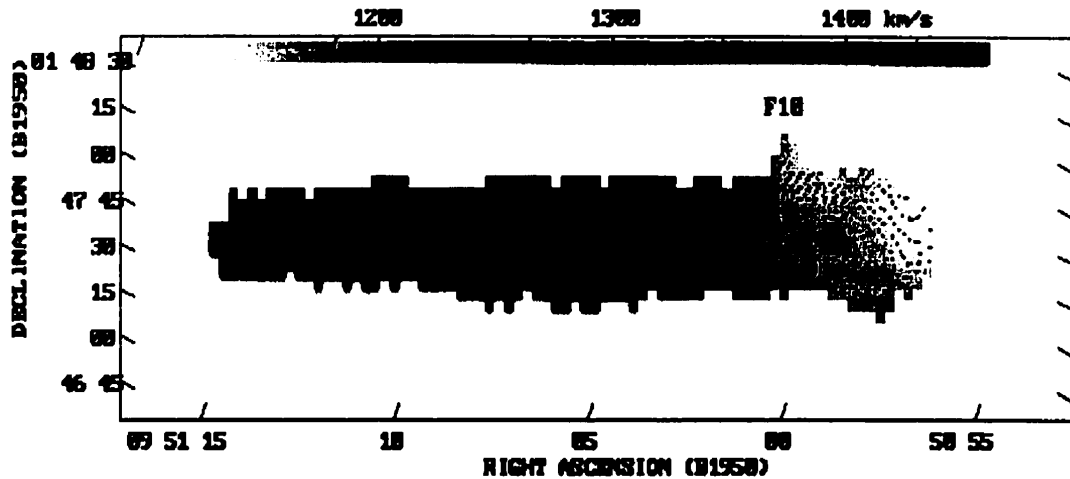


Figure 3.10: Residual velocity field

The contours are obtained by subtracting the velocity field of the model from that of the data. Contours are at $-55, -50, -45, -40, -35, -30, -25, -20, -10, -5, 5, 10, 15$ and 20 km s^{-1} . It is superimposed on the grey scale image of the velocity field of the data for comparison. Grey scale intensities are shown as a band at the top. The cross marks the radio continuum centre of the galaxy and F10 points to the location of Feature 10.

3.4 The CO Distribution in NGC 3044

Molecular gas in galaxies is dominated by molecular hydrogen (H_2). However, H_2 , being a symmetric molecule, does not have a permanent electric dipole moment, hence rotational transitions do not occur. CO is the second most abundant molecule in the interstellar medium. It is a simple diatomic molecule that has a pure rotational spectrum which lies in the millimetre-submillimetre regime and can be easily excited. As a consequence, CO is the most logical choice for tracing the molecular gas distribution.

In order to study the CO distribution in NGC 3044, we obtained $^{12}\text{CO } J=2 \rightarrow 1$ spectra along the galaxy's major axis at positions one half-beamwidth ($10''$ or 1 kpc) apart in the inner region and one beamwidth apart in the outer regions. The total length of the disk observed in $^{12}\text{CO } J=2 \rightarrow 1$ is $190''$ (or 19 kpc). Our observing centre

is at $\alpha = 9^{\text{h}}51^{\text{m}}53^{\text{s}}.0$, $\delta = 1^{\circ}48'57''$, which is about $15''$ west of the radio continuum peak [the position offset closest to the radio continuum peak is at (13.1, 5.3)]. For the purpose of line ratio analysis, we have also obtained spectra around the radio continuum peak to fully sample the area covered by the $45''$ FCRAO ^{12}CO $J=1\rightarrow0$ beam (see §2.2 for details).

3.4.1 CO Spectra

The processed spectra for NGC 3044 are shown in Figure 3.11 for the ^{12}CO $J=2\rightarrow1$ transition and in Figure 3.12 for the ^{12}CO $J=3\rightarrow2$ transition. The single ^{13}CO $J=2\rightarrow1$ spectrum of the galaxy at the offset (13.1, 5.3) is shown in the bottom panel of Figure 3.13. In Figure 3.11, spectrum 14 has the strongest emission. The beam at this position encompasses the radio continuum peak of the galaxy. On the NW side, spectrum 24 displays an interesting triple-peaked feature. The most blue-shifted component in this spectrum (at 1.8σ) is centred at 1070 km s^{-1} , which is not allowed by the normal rotation curve of the galaxy at this position. This may be related to the disturbance occurring in this general region in the HI column density map (Fig. 3.4). The emission lines on the SE side of the galaxy are clearly redshifted and those on the NW side are blueshifted, in agreement with the rotation of the neutral gas (*cf.* §3.3). On the SE side, CO was detected out to about 7 kpc (spectrum 3 in Figure 3.11) and on the NW side to about 5 kpc (spectrum 24). Note however that there may be emission in the most NW spectrum (spectrum 25) at 7 kpc, but low S/N prevents any firm conclusion.

Figure 3.12 shows the 7 spectra obtained at half-beamwidth sampling interval. Spectrum 3 at the offset of (13.1, 5.3) has the strongest line and encompasses the radio continuum peak.

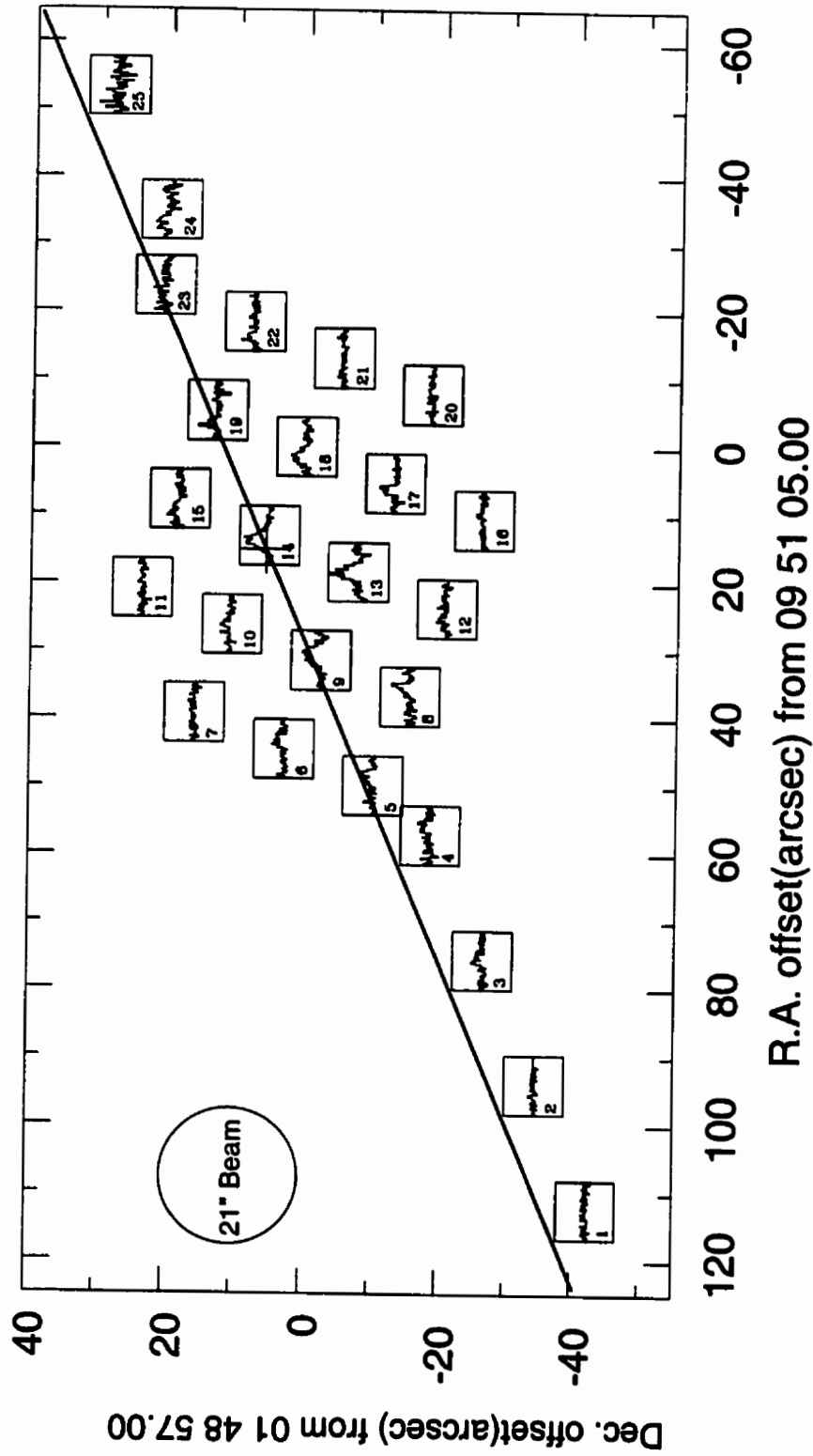


Figure 3.11: Individual ^{12}CO $J=2\rightarrow 1$ spectra of NGC 3044.

Each spectrum shown has LSR velocity from 1050 to 1550 km s^{-1} on the horizontal axis and T_{MB} from -0.1 to 0.1 K on the vertical axis. The cross represents the radio continuum peak of the galaxy and the line across is the major axis ($\text{PA}=113^\circ$).

Figure 3.13 shows the CO emission at offset (13.1,5.3) (closest in position to the radio continuum peak) in all the three observed transitions. The ^{12}CO J=2 $\rightarrow$ 1 spectrum shows emission from 1130 km s^{-1} to 1440 km s^{-1} and a peak intensity of 69 ± 6 mK. A high-velocity (red-shifted) wing extending from about 1360 km s^{-1} to 1440 km s^{-1} is apparent. The peak of the spectrum appears to be flattened with a hint of depression near 1270 km s^{-1} (recall that the systemic velocity is at 1287 km s^{-1}). The ^{12}CO J=3 $\rightarrow$ 2 spectrum is much narrower, with emission from about 1170 km s^{-1} to about 1300 km s^{-1} . The high-velocity side of the spectrum seems to have truncated quite abruptly. The ^{13}CO J=2 $\rightarrow$ 1 spectrum has low S/N (only 1.5). A possible line can be seen from about 1120 km s^{-1} to about 1350 km s^{-1} , almost as wide as the ^{12}CO J=2 $\rightarrow$ 1 line. However, the line shape is difficult to delineate because of the weak signal.

3.4.2 Position-Velocity Diagram

The ^{12}CO J=2 $\rightarrow$ 1 p-v diagram of the major axis slice is shown in Figure 3.14 superimposed on the HI p-v diagram. The width of the slice is $10''$ wide. Both data sets have similar spatial ($\sim 20''$) resolution but the CO channel width is 8 km s^{-1} compared to 20.8 km s^{-1} for the HI data. The peak intensity of the p-v diagram coincides roughly with the RA of the radio continuum peak and $V_{sys} = 1287 \text{ km s}^{-1}$ from the HI global profile (see Table 3.2). The velocity of this peak also agrees, within errors, to the HI modeled V_{sys} (see Table 3.3). Our data barely reach the flat part of the rotation curve with the highest rotation velocities being about $\pm 140 \text{ km s}^{-1}$ with respect to V_{sys} , which is a little less than the HI modeled V_{max} ($150 \pm 3 \text{ km s}^{-1}$). But the difference can be accounted for by the different resolutions of the data as well as the modeled velocity dispersion of the HI gas ($\sigma_v = 24.3 \text{ km s}^{-1}$). Similarly, if we

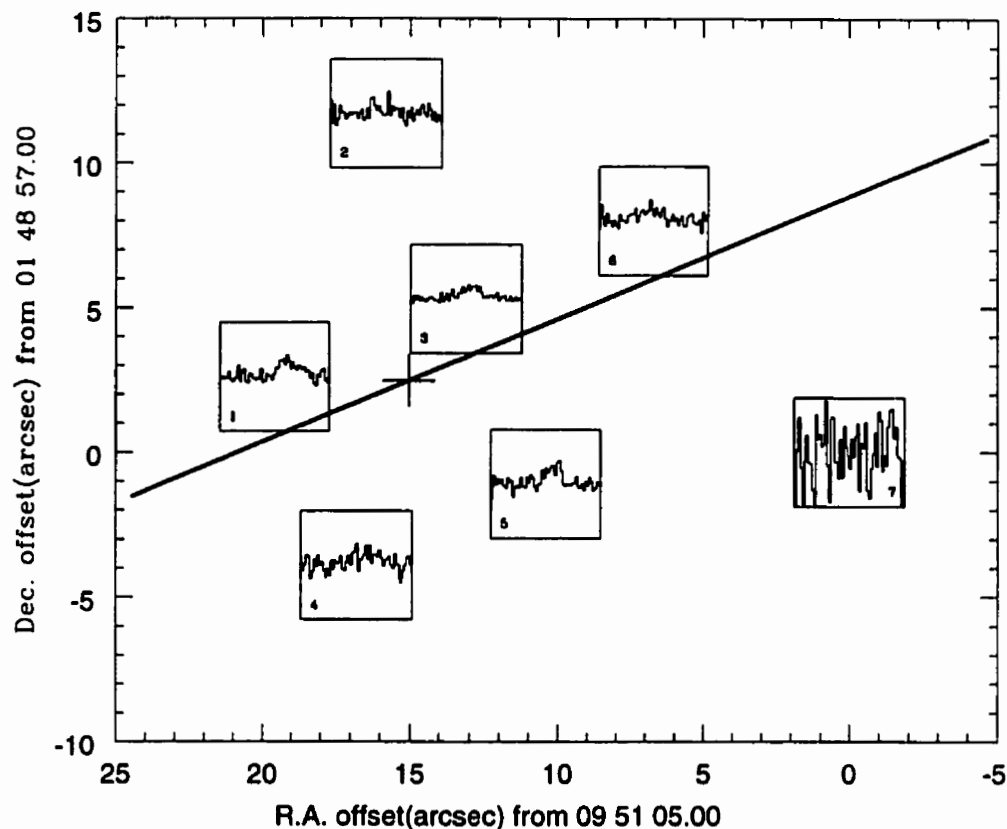


Figure 3.12: Individual ^{12}CO $J=3\rightarrow 2$ spectra of NGC 3044. Each spectrum shown has LSR velocity from 1000 to 1470 km s^{-1} on the horizontal axis and T_{MB} from -0.25 to 0.25 K on the vertical axis. The cross represents the radio continuum peak of the galaxy and the line across is the major axis ($\text{PA}=113^\circ$). The beam HPBW is $14''$ across.

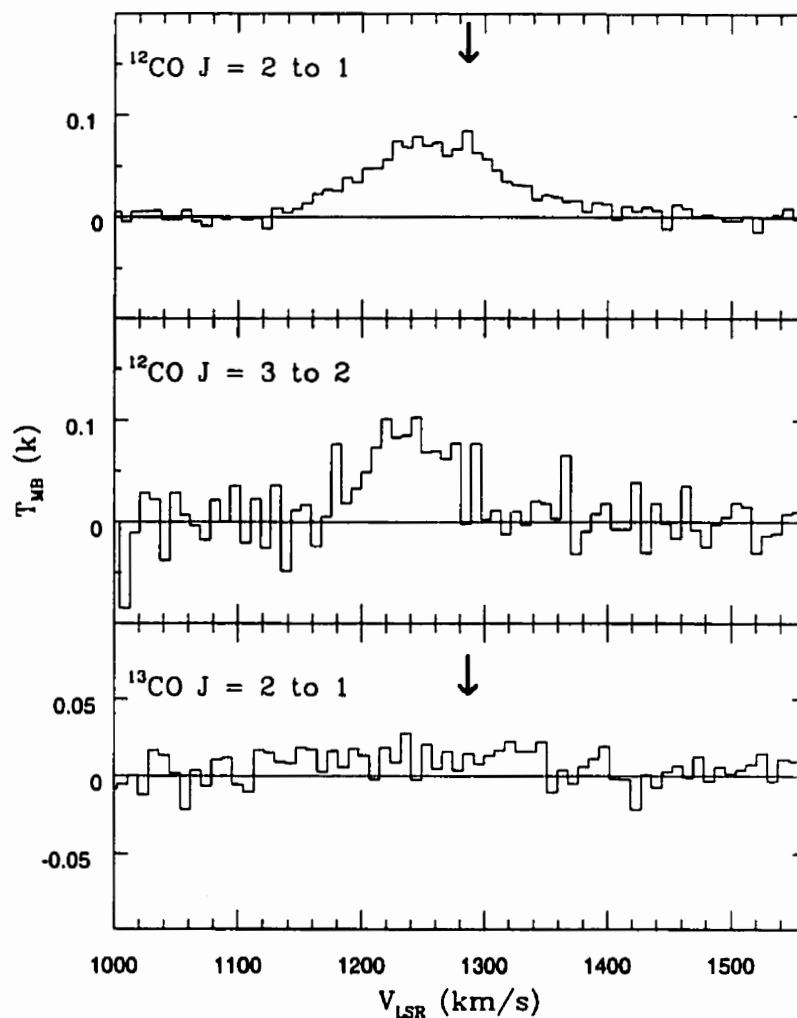


Figure 3.13: Nuclear CO Emission in NGC 3044

The ^{12}CO $J=2\rightarrow 1$ (top panel), ^{12}CO $J=3\rightarrow 2$ (middle panel), and ^{13}CO $J=2\rightarrow 1$ (bottom panel) spectra at the position offset (13.1,5.3) in NGC 3044. The downward arrows indicated the systemic velocity at 1287 km s^{-1} .

take into account the difference in velocity resolutions and velocity dispersion along the line of sight, the gradients of the rotation curves for the two sets of data are in agreement. There appear to be two interesting ‘tails’ along the line of sight at about $\pm 50''$ (± 5 kpc) in the CO p-v diagram. These are detections at $1-2\sigma$ level and may not be real. Higher S/N data are needed to verify their presence.

If we assume the gas kinematics to be dominated by circular rotation (a reasonable assumption for spiral galaxies), then we can estimate the dynamical mass (M_T) of the galaxy from the CO p-v diagram, just as was done for the HI data. Within a radius of 2.3 kpc ($23''$, where the transition from solid body rotation to flat rotation occurs in Figure 3.14), and taking $V_{rot}=140 \text{ km s}^{-1}$, we find $M_T = 1.0 \times 10^{10} M_{\odot}$. This agrees with the HI-inferred dynamical mass within the same radius and constitutes 7% of the dynamical mass within a radius of 15.3 kpc from the HI data (Table 3.2).

3.4.3 Integrated Intensity

For each spectrum, the integrated intensity (in units of K-km s^{-1}) was obtained by summing the intensities over the velocity range where real emission is observed (see Table 3.4). The uncertainty in this quantity is estimated to be about 20%, which includes the uncertainties due to baseline subtraction, flux calibration and the rms noise of the spectrum. A map of integrated intensities was formed and interpolated using the FILL-CUBE routine in the data analysis software GILDAS⁵. The pixels of the map are chosen to be $5''$ squares, hence each ^{12}CO J=2→1 beam contains about 14 pixels. We assume the integrated intensity within a beam is an average across the beam, hence all pixels in the beam are assigned the same value unless

⁵GILDAS, the “Grenoble Image and Line Data Analysis Software”, is a collection of software developed by the Observatoire de Grenoble and the Institut de Radio Astronomie Millimétrique, oriented towards radio astronomy applications.

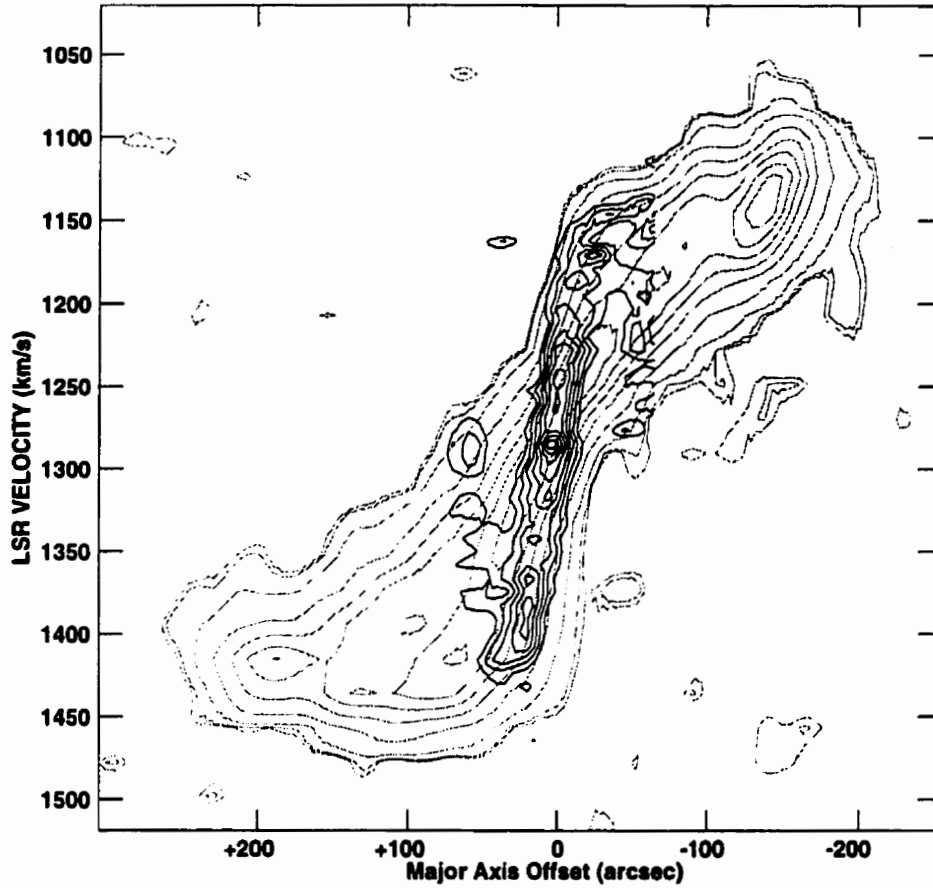


Figure 3.14: ^{12}CO $J=2\rightarrow 1$ Major-axis Position-Velocity Diagram of NGC 3044

The ^{12}CO $J=2\rightarrow 1$ major-axis p-v diagram (black contours) is superimposed on the HI p-v diagram from Figure 3.8 (grey contours). The CO p-v contours is obtained with a slice along the major axis with width of $10''$ and the contour levels are 20 to 100 mK in increment of 10 mK, 120 to 240 mK in increment of 20 mK and 250 mK. The cross represents the radio continuum peak at the systemic velocity. The two p-v diagrams have similar spatial resolutions. The CO data has a velocity resolution of 8 km s^{-1} while the HI data has a velocity resolution of 20.8 km s^{-1} .

Offset	Peak	rms	S/N	Velocity Interval	Integrated	Spectrum ^a
	T_{mb}	Noise		(from to)	Intensity	No.
(arcsecs)	(mK)	(mK)		(km s^{-1})	(K-km s^{-1})	
10.4 -1.1	90	22	4	1219 1304	6.2 ± 0.6	5
19.6 2.6	70	21	3	1238 1400	8.0 ± 0.8	1
6.7 8.0	60	27	2	1121 1284	6.6 ± 1.0	6
15.8 11.7	64	24	3	1170 1301	3.4 ± 0.8	2
16.8 -3.9	82	40	2	1194 1373	7.4 ± 1.5	4
¹² CO J=1→0						
0.0 0.0 ^b	...	...	...	...	9.0 ± 1.1	

^aThe spectrum numbers coincide with the spectrum numbers in Fig. 3.11 and 3.12

^b ¹²CO J=1→0 integrated intensity obtained from Solomon and Sage (1988). This position corresponds to the offset (13.1,5.3) of the JCMT data.

Figure 3.15 shows the interpolated integrated intensity map of NGC 3044 for the ¹²CO J=2→1 transition. The distribution peaks near the radio continuum peak (represented by the cross) and declines linearly along the NW major axis. The orientations of the inner contours do not follow the major axis but curve northward on both the east and west side (i.e., the contours have “kidney” shapes). Near $\alpha = 9^{\text{h}}51^{\text{m}}38.7$, $\delta = 1^{\circ}49'15''$, there appear to be a valley in the CO distribution. Further to the NW, an intensity enhancement [due to the triple-peaked spectrum at (-34.9,20.2)] is seen at $\alpha = 9^{\text{h}}51^{\text{m}}28.6$, $\delta = 1^{\circ}49'15''$ or about 5.6 kpc from the central peak. Although this *suggested* gas pile-up is based on merely one spectrum, we note that the enhancement

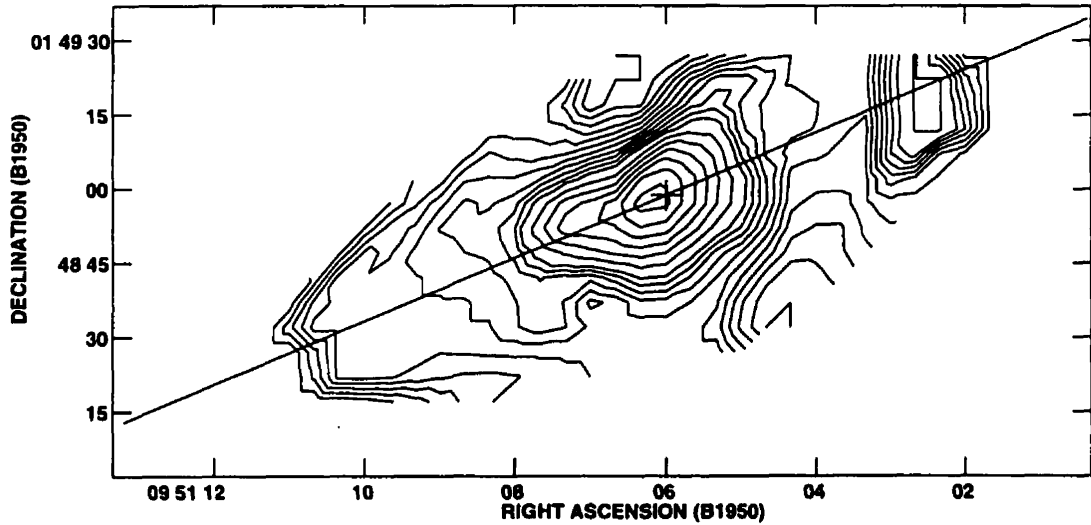


Figure 3.15: Map of ^{12}CO $J=2\rightarrow 1$ Integrated Intensity of NGC 3044. Contours are from 0.0 to 5.0 K-km s^{-1} with increment of 0.5 K-km s^{-1} and 6.0 to 11.0 K-km s^{-1} with increment of 1.0 K-km s^{-1} . The cross represents the radio continuum peak and the line across represents the major axis.

is possibly related to the region of disturbance near F10 (but not directly below F10). This will be discussed in more detail in §3.8. On the SE side the decline from the central peak appears to be more gradual and elongated. The elongation is due to the high-velocity, redshifted wing shown in the top panel of Figure 3.13. We shall not attempt to interpret the distribution at the edge of the map, for the reason stated in the previous paragraph.

The ^{12}CO $J=2\rightarrow 1$ integrated intensities along the major axis are plotted in Figure 3.16. The offsets are plotted with respect to the radio continuum peak and a 20% uncertainty in the values should be kept in mind. The figure shows the integrated intensities fall off sharply on both sides of the peak. Within $+25''$ on the SE and $-15''$ on the NW, the integrated intensities are reduced by 50%. Note that this

behaviour is suggestive of a central molecular disk within roughly 20'' (full-width-half-max or FWHM), equivalent to a radius of 2 kpc. This distribution is similar to that in NGC 4631 which has a central molecular disk of radius 2.5 kpc (Golla and Wielebinski 1994). The integrated intensity rises again starting from about -40'' from the peak. This is due to the relatively strong emission at the (-34.9,20.2) offset.

3.4.4 CO Line Ratios

CO line ratios are important because we can obtain physical parameters of molecular clouds with them. Assuming the gas emitting the different lines has similar spatial and velocity distribution, the ratios of integrated intensities are then equivalent to the ratios of peak radiation temperatures. These line ratios can then give us a handle on the opacities, temperatures and densities of clouds (see the Appendix for definitions and detailed explanations, also see Richardson 1985). Due to NGC 3044 being almost edge-on ($i = 85^\circ$), we essentially “see” right through the molecular disk. It follows that the result of the line ratio analysis is a set of physical parameters which represent the *integrated* properties of the clouds within the beam along the line-of-sight dimension of the molecular disk. However, Figure 3.16 shows that the integrated intensities drop off sharply from the nucleus. If we assume the gas is similarly distributed along the line of sight, then we can conclude that most of the emission come from the central molecular disk. The physical parameters derived would be representative of clouds in this central molecular disk with FWHM of about 2 kpc.

With the JCMT observations, we have obtained two line ratios over equivalent (smoothed) beam, $^{13}R_{21} = \frac{\int T_{MB} d\nu(^{13}CO J=2 \rightarrow 1)}{\int T_{MB} d\nu(^{12}CO J=2 \rightarrow 1)}$ and $R_{32} = \frac{\int T_{MB} d\nu(^{12}CO J=3 \rightarrow 2)}{\int T_{MB} d\nu(^{12}CO J=2 \rightarrow 1)}$, centred at the galaxy’s nucleus. Since the ^{13}CO J=2→1 line has low S/N, its integrated intensity, and hence $^{13}R_{21}$, is an upper limit. $\int T_{MB} d\nu(^{12}CO J = 3 \rightarrow 2)$ is the

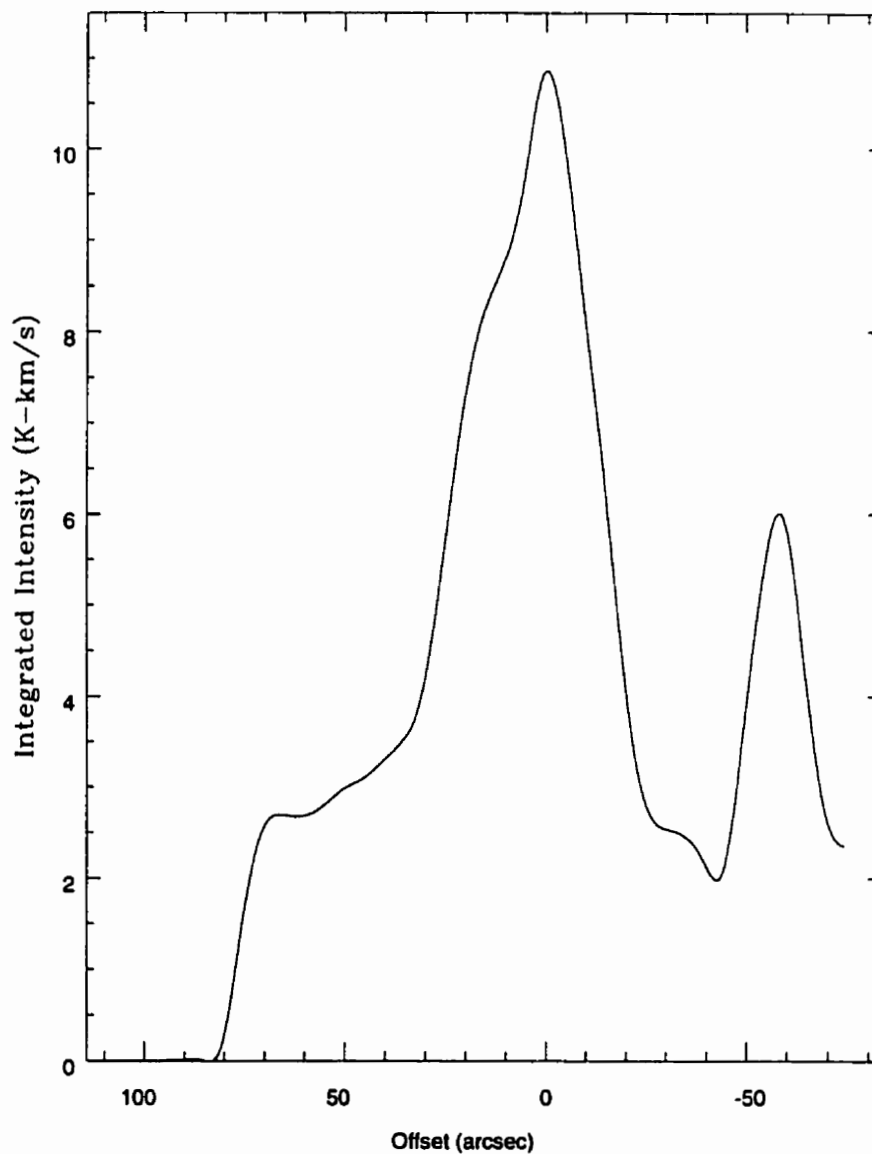


Figure 3.16: ^{12}CO $J=2\rightarrow 1$ Integrated intensity along the major axis
The integrated intensity of the ^{12}CO $J=2\rightarrow 1$ transition along the major axis is plotted. The horizontal axis is plotted as the offsets from the radio continuum peak in arcseconds. 20% uncertainty is associated with each value.

averaged value obtained after the ^{12}CO J=3 $\rightarrow$ 2 map was smoothed to the larger ^{12}CO J=2 $\rightarrow$ 1 beam. Solomon and Sage (1988) obtained, using the FCRAO 14-m telescope, the ^{12}CO J=1 $\rightarrow$ 0 integrated intensity of NGC 3044. As described in Chapter 2, our ^{12}CO J=2 $\rightarrow$ 1 data include complete sampling within the FCRAO 45'' beam. We therefore smoothed the ^{12}CO J=2 $\rightarrow$ 1 data to the ^{12}CO J=1 $\rightarrow$ 0 beam to find the line ratio $R_{21} = \frac{\int T_{MB} d\nu(^{12}\text{CO} J=2\rightarrow 1)}{\int T_{MB} d\nu(^{12}\text{CO} J=1\rightarrow 0)}$. The (0,0) position in Solomon and Sage (1988) is most likely the position listed in the IRAS Point Source Catalogue, which is at $\alpha = 9^{\text{h}}51^{\text{m}}6^{\text{s}}.2$, $\delta = 1^{\circ}48'55''$. This position is only 6''.7 from the strongest JCMT ^{12}CO J=2 $\rightarrow$ 1 spectrum. The integrated intensity given is in the T_R^* temperature scale (see Appendix B) and is 6.4 ± 0.8 K-km s $^{-1}$. In order to compare with the JCMT data, which are in the T_{MB} temperature scale, we have to multiply the FCRAO value by the factor η_{fs}/η_{MB} , where η_{fs} is the forward spillover and scattering efficiency and η_{MB} is the main beam efficiency of the FCRAO telescope. During the period when NGC 3044 was observed, η_{fs} and η_{MB} were 0.7 ± 0.1 and 0.53 ± 0.04 for the 14-m telescope, respectively (L. Sage, private communication and Kenney and Young, 1988). Therefore, the ^{12}CO J=1 $\rightarrow$ 0 integrated intensity used here is 8.5 ± 1.7 K-km s $^{-1}$. Table 3.5 lists the three line ratios and their uncertainties.

We compare the ratio R_{21} in NGC 3044 with the mean ratio found in 60 nearby spiral galaxies reported by Braine and Combes (1992). The mean ratio is 0.89 with a standard deviation of 0.34. Our value here is small by comparison. One explanation is that their observations are obtained with HPBW which is a factor of two smaller (23'' for the ^{12}CO J=1 $\rightarrow$ 0), hence the ratios they obtained reflect the physical conditions within the central 1 kpc radii of the galaxies. If the line ratio has a negative gradient with galactocentric radii (for example, Handa *et al.* 1993 for the Galaxy), then it may very well explain the low value found for NGC 3044. On the other hand, various

Table 3.5: Nuclear CO Line Ratios of NGC 3044

R_{21} ^a	0.41 ± 0.13 smoothed to the $45''$ beam
R_{32} ^b	0.47 ± 0.09 smoothed to the $21''$ beam
$^{13}R_{21}$ ^c	$\leq 0.30 \pm 0.06$ with $21''$ beam

$$^a R_{21} = \frac{\int T_{MB}(^{12}\text{CO } J=2 \rightarrow 1) d\nu}{\int T_{MB}(^{12}\text{CO } J=1 \rightarrow 0) d\nu}$$

$$^b R_{32} = \frac{\int T_{MB}(^{12}\text{CO } J=3 \rightarrow 2) d\nu}{\int T_{MB}(^{12}\text{CO } J=2 \rightarrow 1) d\nu}$$

$$^c ^{13}R_{21} = \frac{\int T_{MB}(^{13}\text{CO } J=2 \rightarrow 1) d\nu}{\int T_{MB}(^{12}\text{CO } J=2 \rightarrow 1) d\nu}$$

other studies within galaxies show no systematic trend in R_{21} with galactocentric radii (Golla and Wielebinski 1994 and García-Burillo *et al.* 1992). The upper limit for the $^{13}R_{21}$ ratio is consistent with values found both for the Galaxy ($^{13}R_{21} \sim 0.2$, Sanders *et al.* 1993) and for a collection of starburst galaxies ($^{13}R_{21} \approx 0.08$, Aalto *et al.* 1995). The R_{32} ratio is close to the Galactic value of 0.55 given by Sanders *et al.* (1993). Interestingly, $R_{32} = 0.55$ is also measured for the outer parts of some molecular clouds (Falgarone *et al.* 1991) and $R_{32} = 0.4$ for translucent clouds (van Dishoeck *et al.* 1991).

The Large Velocity Gradient (LVG) Approximation The simplest way to interpret the observed line ratios is to assume that the clouds are in local thermodynamic equilibrium (LTE). That is, the CO lines are collisionally excited and all lines are thermalized so that the radiation temperature (the physical temperature of the clouds) and the excitation temperature (the temperature that governs the relative population of the different rotational sub-levels of the molecule) are the same as the

kinetic temperature. This approach has traditionally been used to analyse molecular line ratios. However, the conditions in the ISM is considerably more complicated and the LTE condition is a gross oversimplification.

We instead use the LVG model to obtain the physical condition of the molecular clouds. The basic assumption of this model is that the large CO line widths observed in galaxies are due to large-scale inflow motions in the molecular clouds. Hence, photons which are able to escape the vicinity where they are emitted will reach the observer because the large velocity gradient ensures that they will not be re-absorbed elsewhere in the cloud. Using this assumption, the relative rotational level populations of a molecule can be determined and hence the physical parameters of the clouds. A more detail description of the LVG model can be found in Appendix C (see also Goldreich and Kwan 1974, Wall *et al.* 1993).

We first modeled the clouds in NGC 3044 using a one-component LVG code⁶. Given a range of kinetic temperatures, T_k (10 K to 200 K in 10 K steps), density of molecular hydrogen, n_{H_2} (10^2 cm^{-3} to 10^9 cm^{-3} in 0.5 order of magnitude steps), and the fractional abundance of CO per velocity gradient, $X_{CO}/(dv/dr)$ (10^{-10} to $10^{-4} \text{ pc}/(\text{km s}^{-1})$ in 0.5 order of magnitude steps), the code computes the theoretical radiation temperatures, T_R , optical depths, τ , and excitation temperatures, T_{ex} of the observed transitions (see Appendix C for definitions). Theoretical line ratios are then calculated and compared with the observed ratios. The quantity, χ^2 is obtained as a gauge of the goodness of the fit. Collision rate coefficients from Flower and Launay (1985) were used. The abundance of the rarer isotope (^{13}CO) is calculated from the abundance of the main isotope and the relative abundance ratio of ^{12}CO to ^{13}CO .

⁶The original LVG code was supplied by L. Avery of the Herzberg Institute of Astrophysics, National Research Council. The code was subsequently modified by J. Arnett and J. Irwin. into the one- and two-component codes used here.

Langer and Penzias (1990) found a gradient of this ratio from a low value (~ 25) in the Galactic centre, to a high value (70) beyond the solar circle. We therefore try values of 25, 50 and 70 in the models. Since the $^{13}R_{21}$ ratio is an upper limit, we also look for solutions by lowering this ratio by factors of 2, 5, 10 and 20.

Using all line ratios, including the upper limit for the $^{13}R_{21}$ ratio, we did not find any solution which agrees within the uncertainties of the observed ratios. This remains true even if we lower $^{13}R_{21}$ by up to a factor of 20. In column 2 of Table 3.6, we list the best results obtained using the upper limit of $^{13}R_{21}$ to show that the theoretical line ratios (row 5 to 7 in Table 3.6) indeed do not agree with our observations (Table 3.5) to within quoted errors.

A possible explanation for our inability to obtain a solution is that the clouds within the telescope beam are not homogeneous. Wall *et al.* (1993) find it necessary to consider a two-component model for a sample of infrared-bright galaxies. The two components being dense cloud cores and low-density clouds. The latter are either the envelopes of the cloud cores or clouds that are stripped off from the envelopes of the cloud cores by tidal force near the nucleus of the galaxy. In this case, a single component LVG model naturally cannot be sufficient to reproduce the observed line ratios. A more complex model is in order. We therefore employ the simplest two-component LVG model to our data. In this model, the CO emission is still assumed to come from similar clouds but there are two distinct types of clouds, one with one set of parameters (n_{H_2} , $X_{CO}/(dv/dr)$ and T_k) and one with another set. Cloud cores and envelopes are not distinguishable. Although a simpler version than the two-component model used by Wall *et al.* (1993), our model is still superior to the one-component model used above. The emergent radiation temperature is a “mixture” of radiation temperatures from the two components. The mixing of the temperatures

Table 3.6: One-Component Large Velocity Gradient Solutions for NGC 3044

$^{12}\text{CO}/^{13}\text{CO}$	25
T_k (K)	10
n (cm^{-3})	3.2×10^3
$X_{\text{CO}}/(dv/dr)$ pc/(km s $^{-1}$)	1.0×10^{-5}
R_{21} (Theoretical)	1.27
R_{32} (Theoretical)	0.55
$^{13}R_{21}$ (Theoretical)	0.33
$T_r(^{12}\text{CO} J = 1 \rightarrow 0)$	6.4
$T_{\text{ex}}(^{12}\text{CO} J = 1 \rightarrow 0)$	9.8
$\tau(^{12}\text{CO} J = 1 \rightarrow 0)$	16.8
$T_r(^{12}\text{CO} J = 2 \rightarrow 1)$	5.0
$T_{\text{ex}}(^{12}\text{CO} J = 2 \rightarrow 1)$	9.8
$\tau(^{12}\text{CO} J = 2 \rightarrow 1)$	30.1
$T_r(^{12}\text{CO} J = 3 \rightarrow 2)$	2.7
$T_{\text{ex}}(^{12}\text{CO} J = 3 \rightarrow 2)$	8.6
$\tau(^{12}\text{CO} J = 3 \rightarrow 2)$	18.3
$T_r(^{13}\text{CO} J = 2 \rightarrow 1)$	1.6
$T_{\text{ex}}(^{13}\text{CO} J = 2 \rightarrow 1)$	6.2
$\tau(^{13}\text{CO} J = 2 \rightarrow 1)$	1.7

are obtained via

$$T_R = T_R(A) + ff[T_R(B)] \quad (3.14)$$

where $T_R(A)$ and $T_R(B)$ are the radiation temperatures of component A and B, respectively, and ff is the relative filling factor (filling factor is the area in the beam that is covered by the clouds) of component B with respect to component A.

In the two-component model, there are 7 free parameters as compared to only 3 in the one-component model. As we have only 3 line ratios, the parameters are not well constrained in that many possible solutions exist. We first run the 2-component model using trial temperatures ranging from 15 to 195 K in steps of 20 K, and a $^{12}\text{CO}/^{13}\text{CO}$ ratio of 25 (obtained from the best 1-component model, Table 3.6). The ranges and incremental steps for $X_{\text{CO}}/(dv/dr)$ and n_{H_2} are as in the 1-component case. Although many solutions that agree with the observed line ratios (to within the quoted uncertainties) were obtained, we can nevertheless extract some useful information about the cloud conditions by ruling out certain regions of parameter space. The most important result obtained is that for *all* solutions, the density of component A lies between the narrow range from 100 to 1000 cm^{-3} , and the density of component B is *always* higher ($\geq 3.2 \times 10^3 \text{ cm}^{-3}$) than that of component A. This explains why the 1-component model failed to find a solution. Also, all solutions require $X_{\text{CO}}/(dv/dr)$ to be at least $1.0 \times 10^{-9} \text{ pc}/(\text{km s}^{-1})$ for component A or at least $3.2 \times 10^{-9} \text{ pc}/(\text{km s}^{-1})$ for component B. Finally, the filling factor of component B is no more than 10% the filling factor of component A. In contrast, solutions exist for all temperatures tried, hence this parameter is the least constrained.

Interestingly, the best model (the one with the lowest χ^2 value) is one in which both types of cloud have the same kinetic temperature at 35 K, which is the dust temperature we find using the IRAS flux densities at $60\mu\text{m}$ and $100\mu\text{m}$ (see §3.6).

Table 3.7: Two-Component Large Velocity Gradient Solutions for NGC 3044

Parameter	Model 1 ^a		Model 2 ^b	
	Type A	Type B	Type A	Type B
$^{12}\text{CO}/^{13}\text{CO}$	25		25	
R_{21} (Theoretical)	0.41		0.43	
R_{32} (Theoretical)	0.47		0.48	
$^{13}R_{21}$ (Theoretical)	0.30		0.25	
χ^2 fit	0.073		0.93	
ff	1.0×10^{-3}		3.2×10^{-3}	
T_k (K)	35		35	
n (cm^{-3})	1.0×10^2	3.2×10^3	1.0×10^2	3.2×10^4
$X_{\text{CO}}/(dv/dr)$ pc/(km s^{-1})	1.0×10^{-6}	1.0×10^{-4}	3.2×10^{-6}	
$T_r(^{12}\text{CO } J=1 \rightarrow 0)$	0.14	30.3	0.42	30.9
$T_{\text{ex}}(^{12}\text{CO } J=1 \rightarrow 0)$	3.7	33.9	3.9	34.6
$\tau(^{12}\text{CO } J=1 \rightarrow 0)$	0.21	18.3	0.62	5.5
$T_r(^{12}\text{CO } J=2 \rightarrow 1)$	0.040	28.9	0.13	29.4
$T_{\text{ex}}(^{12}\text{CO } J=2 \rightarrow 1)$	3.7	34.3	3.8	34.8
$\tau(^{12}\text{CO } J=2 \rightarrow 1)$	0.12	57.1	0.38	17.2
$T_r(^{12}\text{CO } J=3 \rightarrow 2)$	0.0065	26.2	0.021	26.9
$T_{\text{ex}}(^{12}\text{CO } J=3 \rightarrow 2)$	5.4	33.8	5.2	34.6
$\tau(^{12}\text{CO } J=3 \rightarrow 2)$	0.0088	87.2	0.031	26.3
$T_r(^{13}\text{CO } J=2 \rightarrow 1)$	0.0016	18.9	0.0051	15.5
$T_{\text{ex}}(^{13}\text{CO } J=2 \rightarrow 1)$	3.7	24.5	3.7	32.2
$\tau(^{13}\text{CO } J=2 \rightarrow 1)$	0.0046	4.2	0.014	0.86

^aThis model has the lowest χ^2 value of all the solutions found by letting all 7 parameters in the 2-component LVG model vary.

^bThis model has the lowest χ^2 value of all the solutions with identical temperatures and abundance for the two components. Component A's temperature is fixed at 35 K.

Since the dust grains which are embedded within the molecular clouds essentially re-radiate the energy they absorb from the UV radiation of stars, it follows that the kinetic temperature of the clouds should be very close to the dust temperature, which is heated by the same radiation field. Component A in this particular solution has both lower density and lower abundance compared to component B, which contributes only 0.1% of the total radiation in the beam. This model is listed in Table 3.7 as Model 1.

Having obtained the above solution, we are now justified in fixing the kinetic temperature of one component (A) at the dust temperature. This removes one degree of freedom. Furthermore, since the results are not constrained, simply accepting the solution with the lowest χ^2 value may not be specially meaningful. However, if we are able to find the *simplest* solution, that might in fact be the best solution. By simplest, we mean solutions in which the temperatures and abundances of both types of clouds are the same (we already know that their densities are different). These solutions, then, are just one level more sophisticated (i.e., with 2 extra degrees of freedom, being density of component B and the relative filling factor) than the 1-component case. Fourteen such solutions exist. Of these, we list the one with the lowest χ^2 value in Table 3.7 as Model 2. The density of component B in Model 2 is an order of magnitude higher than that in Model 1 and the abundance for both components in Model 2 is a little higher than that of component A in Model 1. With the current available data, Model 2 represents the “best” model for clouds in NGC 3044.

The two-component LVG analysis therefore concludes that the clouds within the inner 2.3 kpc radius of NGC 3044 can be characterized by a low-density ($\sim 100 \text{ cm}^{-3}$) and a high-density component ($\sim 10^4 \text{ cm}^{-3}$). In addition, we find that the surface density of the dense clouds is no more than 10% that of the low-density clouds. The

simplest solution in which the temperature and abundance of the two types of cloud are the same gives 35 K as the kinetic temperature and 3.2×10^{-6} pc/(km s⁻¹) for the abundance per velocity gradient. 35 K is also the dust temperature derived from far-infrared data, leading us to believe there is a good physical basis for the solution.

The relative abundance of CO to H₂ requires the knowledge of the velocity gradient within a cloud, which we can not obtain with the spatial resolution of our data. If the cloud velocity gradient in NGC 3044 is similar to that of the Galactic clouds [10 to 15 km s⁻¹ pc⁻¹, (Irvine *et al.*, 1987)], then the relative abundance of CO to H₂ is $3.2 - 4.8 \times 10^{-5}$, close to the Galactic dark clouds⁷ value, which is about 5×10^{-5} (Williams 1985). Galactic dark clouds have densities ranging from 100 - 1000 cm⁻³ and temperatures between 15 to 50 K (Turner and Ziurys, 1988). The equivalent parameters for type A clouds given in Table 3.7 suggest that this component may be identified as dark clouds in NGC 3044. It is unclear which component the type B clouds can be identified with. However, given that solutions exist for $n_{H_2} \geq 3.2 \times 10^3$ cm⁻³, there may be a range of density for this component within the beam.

3.4.5 The Molecular Gas Mass

In principle, the molecular gas mass can be obtained from the actual parameters of the clouds found through the LVG modeling. However, here we chose to estimate the mass using the more conventional method (described below) because the LVG parameters are not well constrained (see previous subsection).

The molecular gas mass of a cloud, M_{H_2} , can be obtained from the ¹²CO J=1→0

⁷Dark clouds refer to small molecular clouds which are believed to be low mass star formation sites.

luminosity of the cloud, L_{CO} , via

$$M_{H_2} = L_{CO} \sqrt{\frac{4\rho}{3\pi G}} \frac{1}{T_{MB,p}} \quad (3.15)$$

where ρ is the mass density of the molecular cloud, G is the gravitational constant and $T_{MB,p}$ is the peak main beam temperature. The physical basis for the existence of this conversion factor is the fact that molecular clouds are usually self-gravitating and hence must be in virial equilibrium. Thus, the velocity dispersion in a cloud (σ_v) is given by

$$\sigma_v = \sqrt{\frac{GM_{H_2}}{R_{cl}}}, \quad (3.16)$$

where R_{cl} is the radius of the cloud. Since $L_{CO} = \pi R_{cl}^2 T_{MB,p} \sigma_v$ and $M_{H_2} = 4\pi\rho R_{cl}^3/3$, we obtained equation 3.15. More conveniently, equation 3.15 is usually expressed in terms of the column density of H_2 in cm^{-2} , $N(H_2)$, and the ^{12}CO J=1→0 integrated intensity, I_{CO} in $K\text{-km s}^{-1}$ by

$$N(H_2) = X_{CO} I_{CO}, \quad (3.17)$$

where X_{CO} is the CO-to- H_2 conversion factor and is proportional to $\sqrt{\rho}/T_{MB,p}$. In extragalactic work, individual clouds are usually not resolved, I_{CO} would then be the flux density for the ensemble of clouds within the telescope beam. Using $X_{CO} = 3 \times 10^{20} \text{ cm}^{-2} (K \text{ km s}^{-1})^{-1}$ (Young and Scoville, 1991) and $I_{CO} = 8.5 \pm 1.7 \text{ K-km s}^{-1}$ (see §3.4.4), we find $N(H_2) = (2.6 \pm 0.5) \times 10^{21} \text{ cm}^{-2}$. The molecular mass within the 45'' (4.5 kpc) beam is given by the product of the column density, the beam area and the mean molecular mass per H_2 molecule and can be expressed in terms of values pertaining to NGC 3044 as

$$M_{H_2} = 1.3 \times 10^9 \left(\frac{\mu}{4.34 \times 10^{-24}} \right) \left(\frac{N(H_2)}{2.6 \times 10^{21}} \right) \left(\frac{\theta}{45''} \right)^2 \left(\frac{D}{21.5 \text{ Mpc}} \right)^2 M_{\odot} \quad (3.18)$$

where μ is the mean molecular mass per molecule for solar abundances, θ is the HPBW, and D is the distance of the galaxy. That is, we find $1.3 \times 10^9 M_{\odot}$ within the central 2.3 kpc radius. As a comparison, the H_2 mass within the central 2.5 kpc radius of the edge-on galaxy NGC 4631 is very similar, being $1.2 \times 10^9 M_{\odot}$ after scaling to the CO-to- H_2 conversion factor used here (Gölla *et al.* 1994). An uncertainty of about a factor of 2, dominated by the uncertainty in X_{CO} and in the distance, should be kept in mind.

The “universal” factor X_{CO} has been a subject of considerable debate. Values obtained from various independent measurements typically vary from about 1×10^{20} to $5 \times 10^{20} \text{ cm}^{-2} (K - \text{km s}^{-1})^{-1}$ (see review by Young and Scoville, 1991). These values are obtained for the Galactic clouds but can probably be used for clouds in external galaxies of similar Hubble types since metallicity appears to have the largest effect on this factor compared to other cloud properties (Wilson, 1995; Sakamoto, 1996). In addition, large spiral galaxies probably have a radial metallicity gradients across the disks, hence X_{CO} may change radially as well.

The total molecular mass in the galaxy can be estimated using the ^{12}CO J=2→1 data as we have a fairly large coverage of the galaxy in this transition. The total integrated intensity is obtained from Figure 3.15. It was first averaged into 20'' bin (^{12}CO J=2→1 HPBW) and then summed. The total integrated intensity is 77 K-km s⁻¹ within a region 15 kpc across. If we assume that $R_{21} = 0.41$ is constant throughout the molecular disk, then the corresponding ^{12}CO J=1→0 total integrated intensity is 188 K-km s⁻¹. Applying equation 3.18 with $\theta = 20''$, the total molecular mass is found to be $5.7 \times 10^9 M_{\odot}$. This mass is a lower limit since we did not map the outer parts of the galaxy, and because the most northwesterly spectrum shows marginal detection which indicates that there may be more molecular gas beyond this

region. In addition, the rise in integrated intensity at offset $-50''$ in Figure 3.16 may cause the R_{21} to decrease in this region if the $^{12}\text{CO } J=1\rightarrow 0$ intensity does not increase proportionally, hence deepens our underestimate of the total mass. Note that in the calculation of M_{H_2} we did not factor in the effect of lower S/N for the observations furthest away from the nucleus. However, since the integrated intensities drop by a factor of 2 within about $\pm 20''$ from the peak (see Figure 3.16), the contribution of the outer beams are small compared to the uncertainty inherent in the calculation. All considered, we believe our total molecular mass is probably reasonable to within a factor of 3.

The total molecular mass in NGC 3044 is almost a factor of 5 larger than the total molecular mass in the Galaxy ($1.2 \times 10^9 M_{\odot}$ within 10 kpc radius, Bronfman *et al.* 1988) and in NGC 4631 ($1.6 \times 10^9 M_{\odot}$ within about 8 kpc radius, Golla and Wielebinski 1994) and is comparable to that in NGC 891 ($6.3 \times 10^9 M_{\odot}$ within 12 kpc radius, García-Burillo *et al.* 1992), all scaled to the X_{CO} value used here. The various masses of NGC 3044 are listed in Table 3.8. Comparing the inner region and the galaxy as a whole, we find that 23% of the molecular mass is concentrated in the central 2.3 kpc region. In addition, the total molecular mass makes up only 4% of the dynamical mass while in the central 2.3 kpc radius, the molecular mass makes up 13% of the dynamical mass. We estimated the HI mass within the 2.3 kpc region by smoothing the HI naturally weighted data to the $45''$ beam and then integrating the flux over all channels. We find this mass to be $(1.04 \pm 0.03) \times 10^9 M_{\odot}$. All derived masses are listed in Table 3.8. The dust mass is calculated using the far-infrared fluxes obtained by the IRAS satellite (see §4.5).

Within the inner 2.3 kpc region, the total gas mass (HI plus H_2) makes up 23% of the dynamical mass in the same region. In this region, the molecular gas and the

Table 3.8: Derived Masses of NGC 3044

Total Dynamical Mass ^a	$1.5 \times 10^{11} M_{\odot}$
Total M(HI) ^a	$5.3 \times 10^9 M_{\odot}$
Total M _{H₂}	$5.7 \times 10^9 M_{\odot}$
Inner Dynamical Mass (2.3 kpc Radius)	$1.0 \times 10^{10} M_{\odot}$
Inner M(HI) (2.3 kpc Radius)	$1.0 \times 10^9 M_{\odot}$
Inner M _{H₂} (2.3 kpc Radius)	$1.3 \times 10^9 M_{\odot}$
Total Dust Mass ^b	$2.8 \times 10^6 M_{\odot}$

^a From Table 3.2

^bDust Mass is derived from the IRAS fluxes in §3.6

atomic gas are roughly equal by mass. Globally, the total gas mass is only 7% of the dynamical mass. The molecular gas is again roughly equal to the atomic gas by mass globally. Therefore, the gas dynamics in the central region are much more important than in the disk. We compare these ratios to the statistics in the review by Young and Scoville (1991). The gas to dynamical mass as a global parameter shows systematic variation with galaxy type, with later type galaxies having higher ratios. For Sc galaxies, a range of values are found, from a high of 22% to a low of 4% with a median value of 16%. NGC 3044 fits into the low end of the distribution. The M_{H₂}/M(HI) ratio also differs with galaxy type, with later type galaxies having lower ratios. Young and Scoville (1991) attribute this to the more efficient formation of molecular clouds in early type galaxies. However, it is also equally possible that later type galaxies are more efficient in destroying molecular clouds via outflows (Nakai *et al.* 1987) or efficient star formation (such as in starburst galaxies). The ratio of about 1 for NGC 3044 is very near the median value of 0.5 for Sc galaxies in Young and Scoville. Finally, the global gas-to-dust ratio in this galaxy is 3900. This is much

higher than the value used for the Galaxy which is about 150. In IRAS galaxies with warm dust, a mean value of about 1000 is found (see Young and Scoville 1991 and references therein). The total gas mass is a lower limit since the H_2 mass is itself a lower limit, hence deepening the discrepancy. Young and Scoville attribute this discrepancy to the insensitivity of the IRAS bands to detect cold (< 30 K) dust, which may be the bulk of the dust emission.

3.5 The Radio Continuum Emission in NGC 3044

Radio continuum emission below about 10 GHz is dominated by synchrotron radiation from relativistic electrons spiraling along magnetic field lines. The source of these electrons is probably sites of supernovae (Duric 1991) and their distribution depends on transport mechanisms such as diffusion, energy loss, convection or a combination of these (see Duric *et al.* 1997). The radio continuum emission of NGC 3044 has been mapped in 6- and 20-cm by Sorathia (1994). These are shown in Figure 3.17, Figure 3.18 and Figure 3.19. Relevant results are reproduced in Table 3.9. The results of this study show that the radio continuum emission in NGC 3044 is centrally peaked and extended along the minor axis. It has a radio continuum thick disk (emission can be traced up to several kpc) as well as a radio halo (emission beyond several kpc, see Table 3.9). The distribution is asymmetric with the NW side more extended than the SE side. Figure 3.17 also shows evidence of high latitude discrete features at $\alpha = 9^h51^m8^s, \delta = 1^\circ49'30''$, $\alpha = 9^h51^m3^s, \delta = 1^\circ49'30''.5$, and $\alpha = 9^h51^m5^s, \delta = 1^\circ48'0''$.

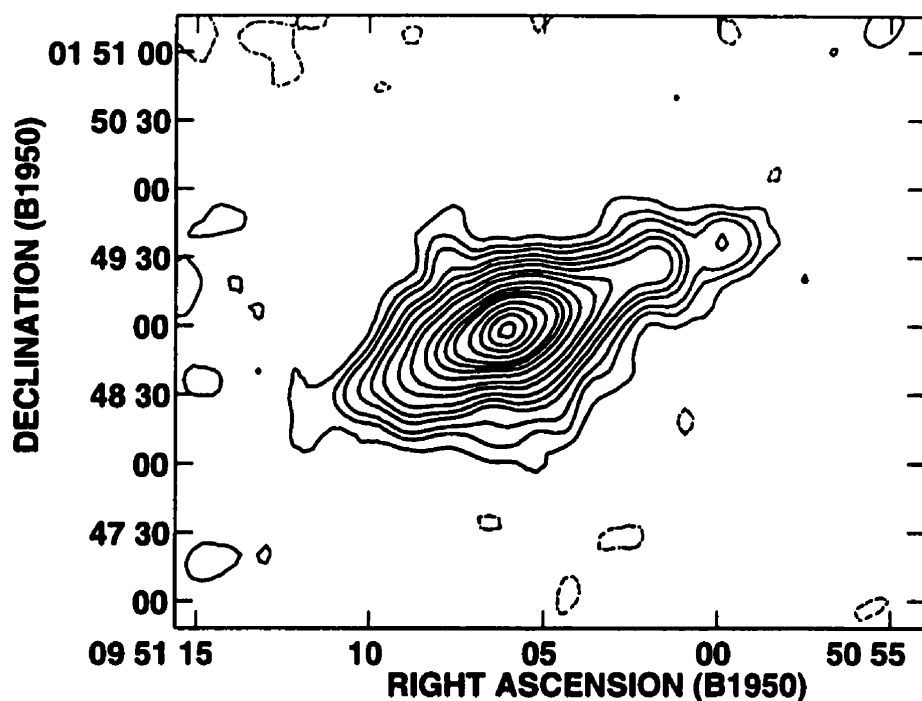


Figure 3.17: 20 cm C-array Radio Continuum Map of NGC 3044 (Natural Weighting) Contour levels are -0.2, 0.2, 0.3, 0.4, 0.7, 1.0, 1.5, 2.2, 2.9, 4.4, 5.8, 7.3, 8.8, 11.7, 14.6, 17.5, 20.4, 21.9 mJy/beam. Adopted from Sorathia (1994).

3.6 The Far Infrared Emission in NGC 3044

The far-infrared data in the 12, 25, 60 and 100 μ m wavebands obtained by the Infrared Astronomical Satellite (IRAS) trace warm dust ($T_{dust} \gtrsim 30$ K) in the disks of galaxies (see, for example, Soifer *et al.* 1984). The dust can be heated by one or both of the following sources: radiation from embedded early-type stars or the local ambient radiation field produced by intermediate-age stars. For NGC 3044, the IRAS flux densities at $S_{60\mu m}$ and $S_{100\mu m}$, given by Soifer *et al.* (1989), are 10.47 Jy and 21.16 Jy, respectively. The quoted flux densities have about 10% uncertainties and are not colour-corrected (i.e, a power-law energy spectrum with spectral index

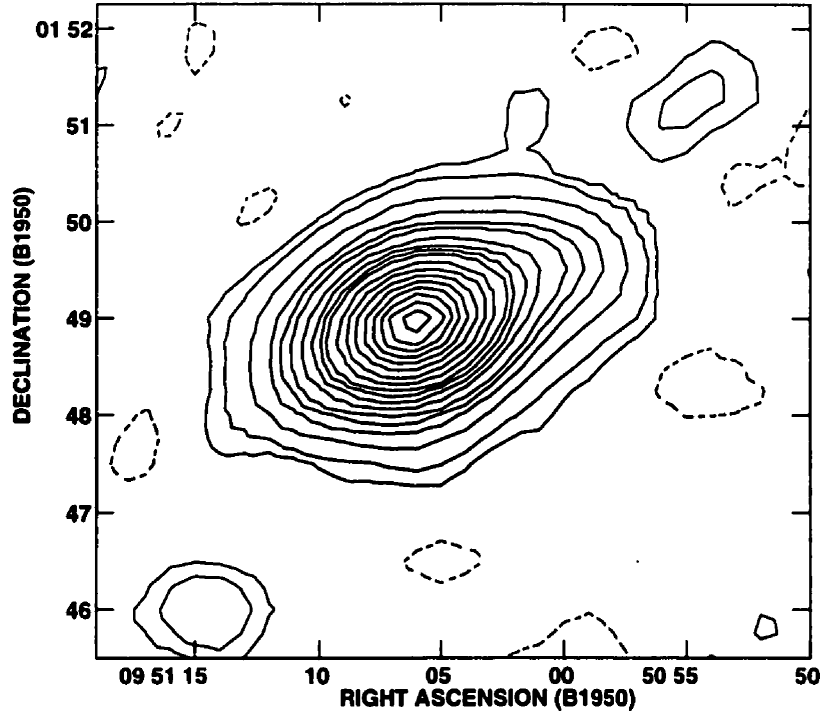


Figure 3.18: 20 cm D-array Radio Continuum Map of NGC 3044 (Uniform Weighting) Contour levels are -0.2, 0.2, 0.4, 1.0, 2.0, 3.0, 4.0, 6.0, 8.0, 10.0, 12.1, 16.1, 20.1, 25.1, 30.2, 35.2, 40.2, 45.2, 50.3, 55.3, 60.3 mJy/beam. Adopted from Sorathia (1994).

of -1 is assumed) since changes in spectral index between 0 and -2 result in a colour correction factor of $\leq 10\%$ (IRAS Explanatory Supplement 1988).

Following Hildebrand (1983), we calculate the dust temperature in NGC 3044 using the equation

$$S_\nu = N \left(\frac{\sigma}{D^2} \right) Q_\nu B(\nu, T_d) \quad (3.19)$$

where N is the number of spherical dust grains, σ is the cross-section of each dust grain, D is the distance of the galaxy, Q_ν is the dust emissivity at frequency ν and $B(\nu, T_d)$ is the blackbody intensity at frequency ν and dust temperature T_d . The dust temperature can be obtained by taking the ratio of the above equation for two

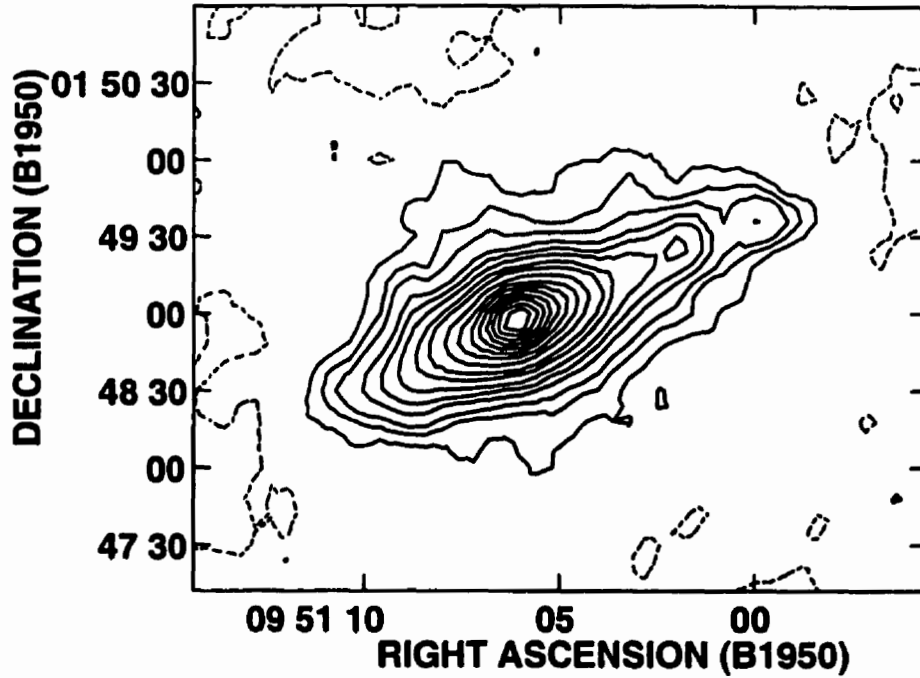


Figure 3.19: 6 cm D-array Radio Continuum Map of NGC 3044 (Natural Weighting) Contour levels are -0.1, 0.1, 0.2, 0.3, 0.5, 0.6, 0.9, 1.4, 1.8, 2.7, 3.7, 4.6, 5.5, 6.4, 7.3, 8.2, 9.2 mJy/beam. Adopted from Sorathia (1994).

different frequencies. Assuming a single temperature component, a λ^{-1} emissivity law (see e.g., Erickson *et al.* 1981; Schwartz 1982) and using the ratio of the 60 to $100\mu\text{m}$ flux densities, the dust temperature is found to be 35.1 K. Compared with the sample of 182 disk galaxies in Young *et al.* (1989), the dust temperature in NGC 3044 lies near the median value.

The $100\mu\text{m}$ dust mass is

$$M_d = [S_\nu D^2 / B(\nu, T_d)] [(4/3)a / Q_\nu] \rho, \quad (3.20)$$

where M_d is the dust mass, and ρ and a are the density and the weighted average size of dust grains, respectively (Hildebrand 1983). Following Young *et al.* (1989), we use

Table 3.9: Radio Continuum Results of NGC 3044

Parameter	Weighting	20 cm C-array	20 cm D-array	6 cm D-array
Total Flux Density (mJy)	Natural	90±3	106±3	42±7
Semi-minor axis extent ^a (kpc)	Uniform	3.67, 3.5 ^b	...	...
	Natural	...	8.34, 7.77	...

^aProjected distances, corrected for beam smearing effect.

^bThe first value refers to the semi-minor axis on the northeastern side of the major axis and the second value refers to the southwestern side.

the values in Table 1 of Hildebrand (1983) to obtain $(4/3)a\rho/Q_{100} = 0.04 \text{ g cm}^{-2}$. Equation 3.19 therefore becomes

$$M_d = 4.79 S_{100} D^2 (e^{143.84/T_d} - 1), \quad (3.21)$$

where M_d is in $M_\odot$, S_{100} in Jy, D in Mpc and T_d in K. Using the values above, we find for the galaxy as a whole, $M_d = (2.8 \times 10^6) M_\odot$.

The total infrared luminosity (from 1 to 1000 μm) of this galaxy is found to be $(1.2 \times 10^{10}) L_\odot$ using

$$L_{IR} = 3.06 \times 10^{19} D^2 C(FIR) \quad (3.22)$$

where FIR is the total flux between 40 to 120 μm given by

$$1.26 \times 10^{-14} (2.58 S_{60\mu m} + S_{100\mu m}) \text{ W m}^{-2} \quad (3.23)$$

and C is the correction factor that accounts for the flux $<40 \mu m$ and $>120 \mu m$ and is listed in Lonsdale *et al.* (1985) as a function of the 60 to 100 μm flux ratio. For

Table 3.10: Far Infrared Parameters of NGC 3044

$S_{60\mu m}$	10.47 Jy
$S_{100\mu m}$	21.16 Jy
T_d	35.1 K
L_{IR}	$1.2 \times 10^{10} L_{\odot}$
M_{dust}	$2.6 \times 10^6 M_{\odot}$
SFR	$0.78 M_{\odot} yr^{-1}$

NGC 3044, C is given by 1.4. Following Condon (1992), we also calculate the massive star formation rate (SFR) for this galaxy using the far-infrared luminosity from

$$SFR = 9.1 \times 10^{-11} L_{FIR}, \quad (3.24)$$

where L_{FIR} is the far-infrared luminosity (i.e., L_{IR} without the correction factor C) in $L_{\odot}$ and SFR is in units of $M_{\odot} yr^{-1}$. The IRAS flux densities and various infrared derived parameters are listed in Table 3.10.

We have also obtained high-resolution IRAS (HIRES) images (Figure 3.20) in the 12, 25, 60 and 100 μm bands from IPAC in order to investigate the far-infrared to radio continuum correlation within the galaxy (see below). The peaks of the 25, 60 and 100 μm HIRES maps are identical to the IRAS position listed in the IRAS Point Source Catalog (1988) ($\alpha = 9^h 51^m 6^s.2$, $\delta = 1^{\circ} 48' 55''$), which has an uncertainty given by an ellipse with semi-major and minor axes of 29'' and 6'', respectively. The major axis of this ellipse has a position angle of 110° and encompasses all the peaks (HI column density peak, modeled centre, optical centroid, and HI kinematic centre) shown in Figure 3.6. The 12 μm map shows a different distribution compared to the other three IRAS wavebands. There are two peaks on either side of the IRAS

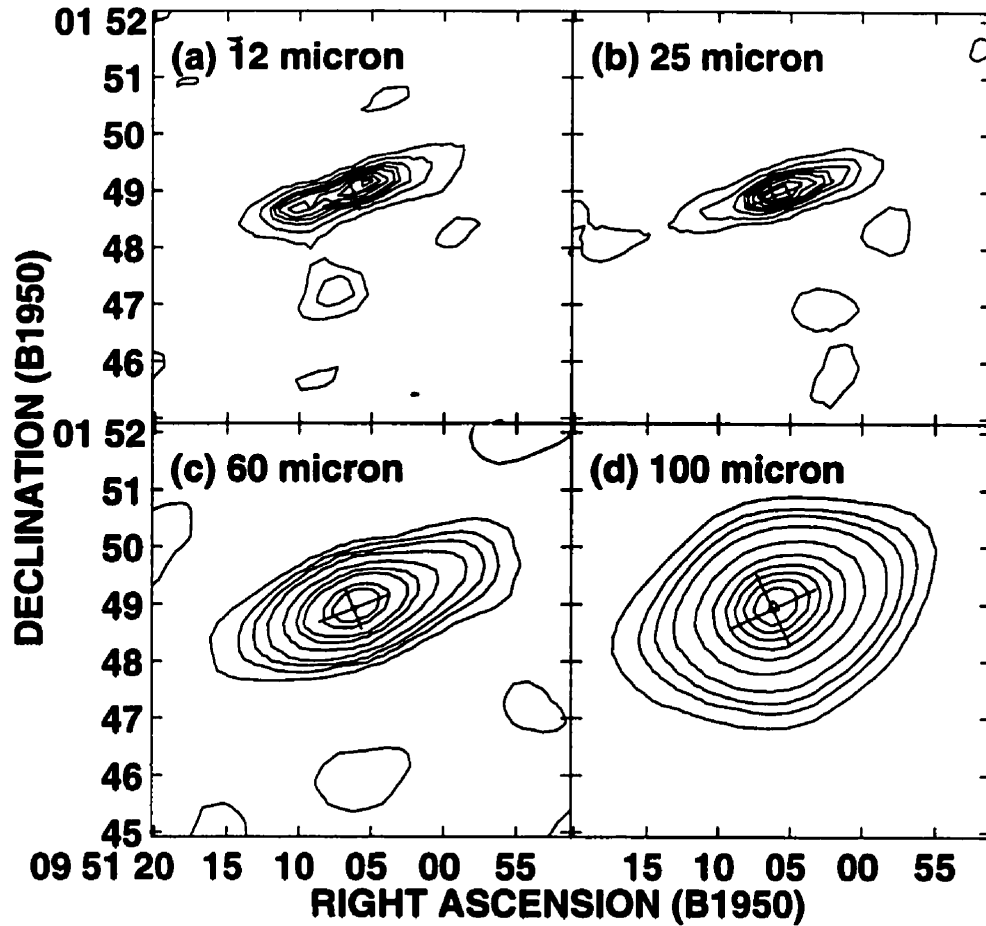
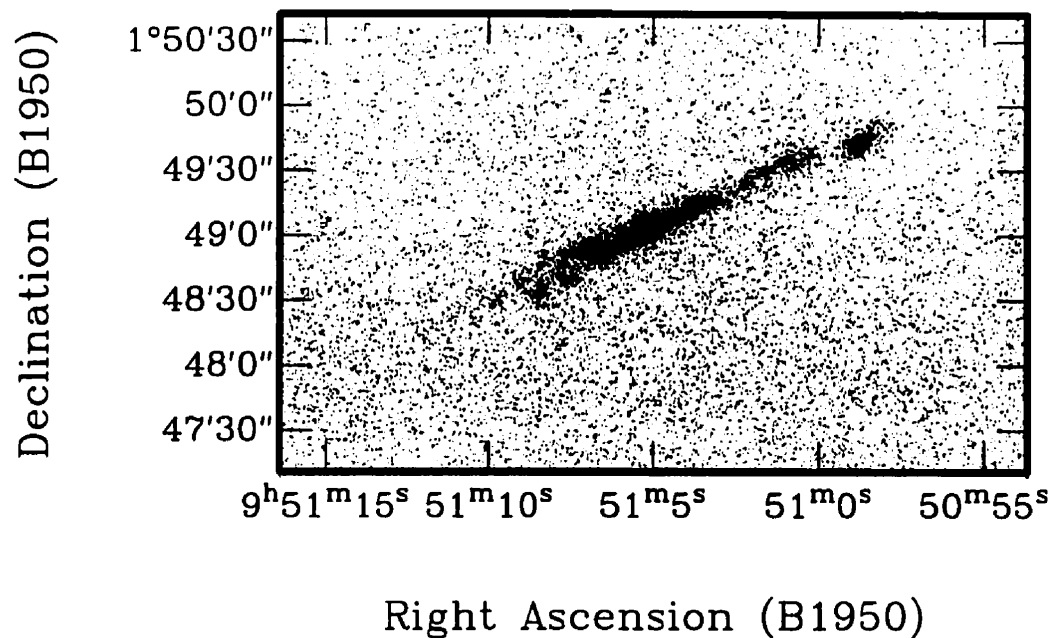


Figure 3.20: High-Resolution IRAS Maps of NGC 3044

(a) $12\mu\text{m}$ map. Contour levels are at 0.6 (2σ), 1.5, 2.4, 3.0, 3.6, 4.5, 5.4, 6.0 MJy/ster. (b) $25\mu\text{m}$ map. Contour levels are at 1.2 (2σ), 2.9, 4.6, 5.8, 7.0, 8.7, 10.5, 11.6, 13.9 MJy/ster. (c) $60\mu\text{m}$ map. Contour levels are at 0.2(1σ), 0.9, 1.8, 3.6, 9.1, 18.1, 27.2, 54.3, 72.4 and 108.6 MJy/ster. (d) $100\mu\text{m}$ map. Contour levels are at 0.2(1σ), 1.2, 2.4, 4.9, 12.2, 24.3, 36.5, 48.6, 60.8, 72.9 and 85.1 MJy/ster. The cross in each panel marks the IRAS position given in the IRAS Point Source Catalog (1988) and the restored beam size and orientation of that waveband.

position with the stronger NW peak at ($\alpha = 9^{\text{h}}51^{\text{m}}53^{\text{s}}$, $\delta = 1^{\circ}49'9''$) near (within half a beamwidth) but not centred at the IRAS position. The SE peak at ($\alpha = 9^{\text{h}}51^{\text{m}}10^{\text{s}}$, $\delta = 1^{\circ}48'40''$) does not coincide with any of the other peaks in Figure 3.6.

Figure 3.21: H α Image of NGC 3044

This image is not flux-calibrated, hence the grey-scale intensity is in arbitrary units which is related to the flux linearly.

3.7 The H α Emission in NGC 3044

H α image of NGC 3044 was supplied by Duric and Grashuis (see §2.5 for observing details). The image has been continuum-subtracted by the observers and we have removed any cosmic ray pixels but it was not flux-calibrated. Figure 3.21 displays this image.

3.8 Multiband Correlations

It is often useful to compare the distributions of the different components of the ISM in a galaxy in order to have a complete view of the galaxy as a whole. In this section, we present superpositions of maps of different wavebands to find any correlations (or anti-correlations) between them.

In Figure 3.22, we compare the HI distribution with the 20-cm C-array radio continuum map (which are of similar beam sizes). In the disk, the HI is more extended (with respect to the kinematic centre of the galaxy) on the SE while the radio continuum is more extended on the NW. The most north-westerly HI column density peak ($\alpha = 9^h51^m0^s.0$, $\delta = 1^\circ49'35''.8$, see also Fig. 3.5) has a counterpart in the radio continuum but not the SE HI peak. At high latitude, the three radio continuum protrusions mentioned in §3.5 appear to be related to F3, F6 and F10 (listed in Table 5.1) in the HI. The radio continuum feature toward F6 partially overlaps the western limb of F6 (see Chapter 5). F3 and F10 both have complex features so that it is difficult to specify precisely what spatial correlations they have with the radio continuum features.

Figure 3.23 displays the overlays of the 4 HIREs maps on the HI natural weighting column density map. There is no obvious correlation between the neutral gas distribution and the dust emission in the disk. The two peaks on the $12\mu m$ map lie on either side of the central HI peak. There is a possible correlation between the detached HI high latitude feature F5, at $\alpha = 9^h51^m7^s.7$, $\delta = 1^\circ47'21''$. The 25, 60 and $100\mu m$ distributions do not have high enough resolution to reveal any finer details in order to compare with the HI data.

Figure 3.24 shows the CO intensity contours superimposed on the HI naturally

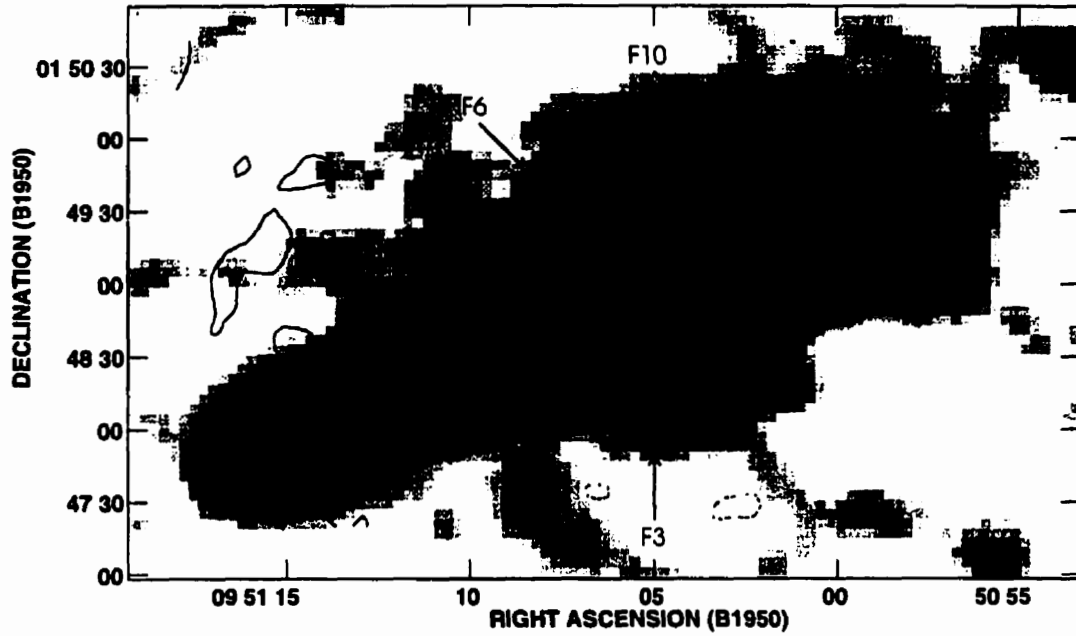


Figure 3.22: Comparing the HI and Radio Continuum Distribution of NGC 3044
 20-cm C-array radio continuum contour map is superimposed on the natural weighted HI column density map. The radio continuum contours are at -0.15, 0.15 (1σ), 0.30, 0.45, 0.75, 1.05, 1.50, 2.25, 3.00, 4.50, 6.00, 7.50, 9.00, 12.00, 15.00, 18.00, 21.00, and 22.50 mJy/beam. A cross marks the radio continuum centre of the galaxy.

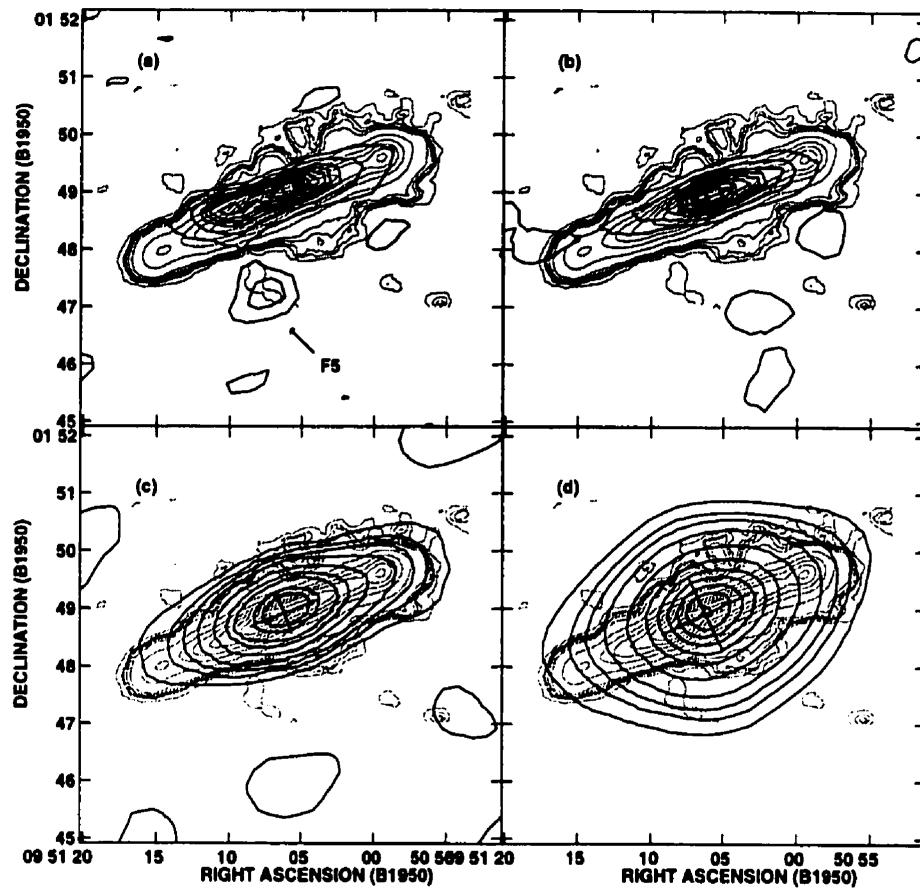


Figure 3.23: HI and Far Infrared Correlation in NGC 3044

The 4 HIRES contour maps (black contours) [(a) 12 μm , (b) 25 μm , (c) 60 μm and (d) 100 μm , as in Figure 3.20] are each superimposed on the naturally weighted HI column density map (grey contours). The contour levels are as in Figure 3.5 for HI and as in Figure 3.20 for HIRES.

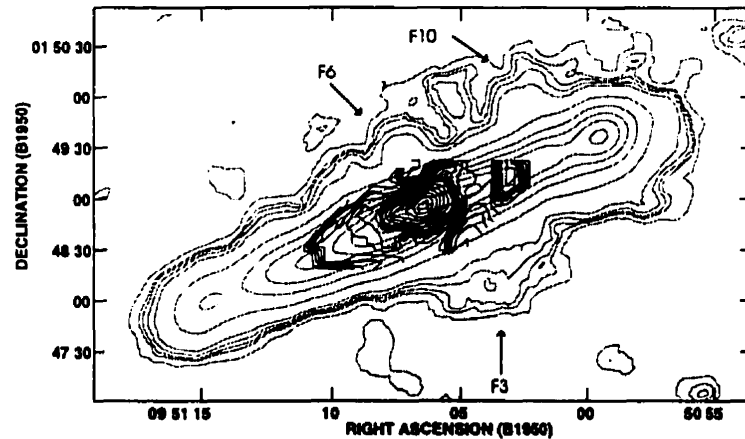


Figure 3.24: Comparing the HI and CO Distribution of NGC 3044

The ^{12}CO $J=2\rightarrow 1$ integrated intensity map (Figure 3.15) is superimposed on the naturally weighted HI column density contour map (Figure 3.5). The cross represents the radio continuum peak of the galaxy.

weighted column density contours (both have similar beam sizes). On the NW side, the CO contours curve northward towards the region of disturbance. It may be related to a high-latitude feature to the east of F10. The NW peak in CO does not correspond to any feature in particular on the HI disk. There are hints of high latitude CO which may correlate with F3 and F6 in the HI. If high latitude CO does indeed exist in these HI features, then star formation may either have started or may begin in the near future. A search for high latitude CO in this galaxy may well proved to be fruitful and should be a high priority in the future.

Figure 3.25 and 3.26 show the $\text{H}\alpha$ grey-scale image, smoothed to the resolution of $20''$, superimposed on the HI column density map and the 20-cm C-array radio continuum map, respectively. These two figures show that in the disk, the $\text{H}\alpha$ distribution correlates better globally with the radio continuum than with the HI in the sense that it is more extended to the NW. But here the correlation ends. The peak

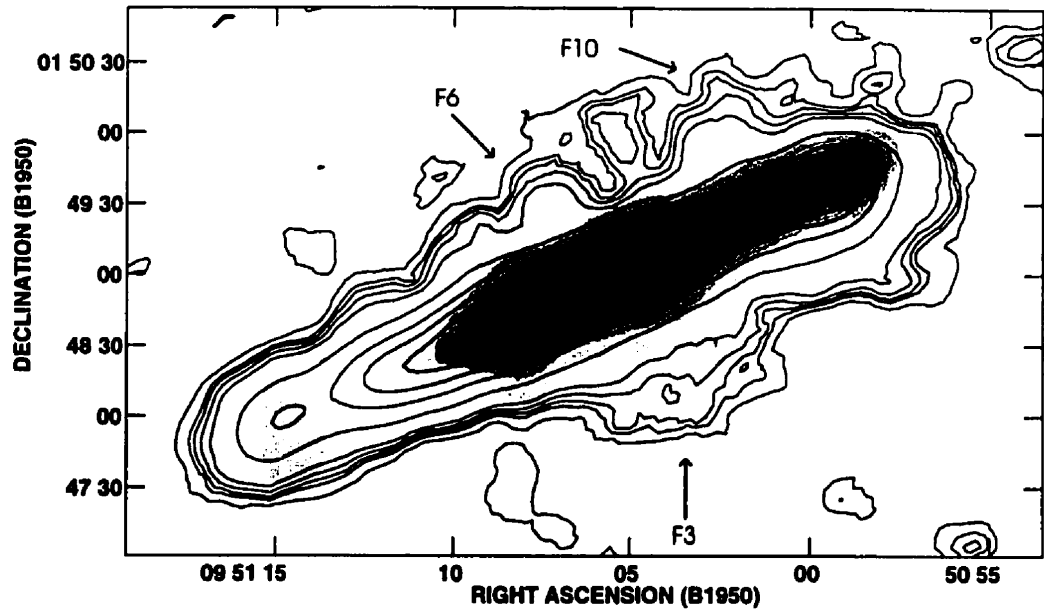


Figure 3.25: Comparing the HI and H α Distribution of NGC 3044
The naturally weighted HI column density contour map (Figure 3.5) is superimposed on the continuum-subtracted H α grey-scale image of NGC 3044.

of the H α distribution is east of the radio continuum peak (or the kinematic peak), probably due to dust absorption. There are two sub-peaks in the H α distribution to the NW, but they do not coincide with the NW peaks in HI and in radio continuum. In fact, in projection, they appear to “sandwich” the peaks in HI and in radio continuum. Furthermore, there appears to be two high latitude features in H α as well, one resembles an open-topped loop towards the direction of F6 and the other may be related to F3. This has interesting implication regarding the HI supershells and is discussed in Chapter 6.

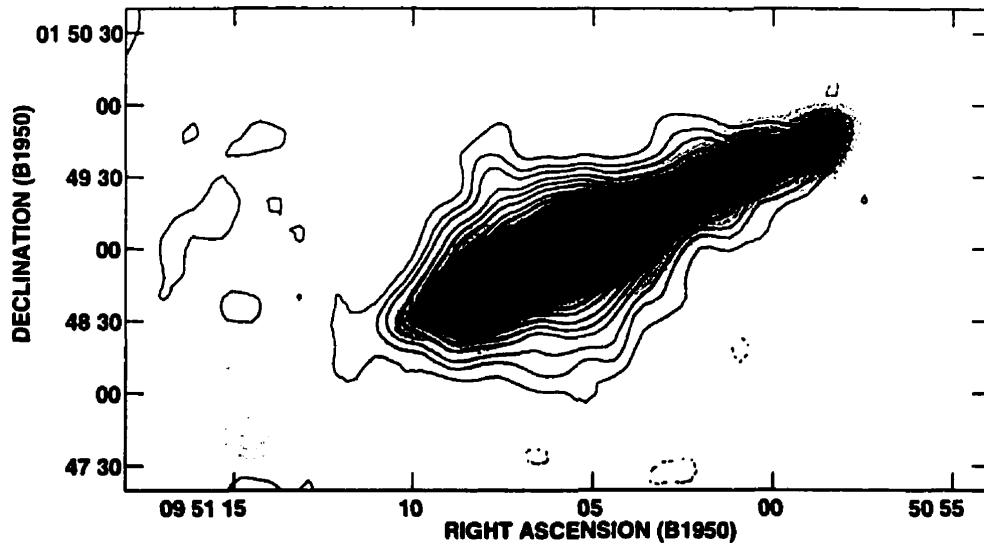


Figure 3.26: Comparing the $H\alpha$ and Radio Continuum Distribution of NGC 3044. The 20-cm C-array radio continuum map is superimposed on the continuum-subtracted $H\alpha$ grey-scale image of NGC 3044.

3.8.1 The FIR-Radio Continuum Correlation

The correlation between the global FIR and radio continuum fluxes of spiral galaxies has long been established. This correlation holds over four orders of magnitude in galaxies luminosity (e.g., Helou *et al.* 1985, Condon 1992 and references therein). In addition, such a correlation has also been seen to hold spatially within galaxies (e.g., Beck and Golla 1988, Bica *et al.* 1989). In the latter cases, peaks of FIR emission typically coincide with local maxima of radio emission within the disks and the ratio of FIR/radio fluxes declines as a function of radius. In the Milky Way Galaxy, where very high resolution observations are possible, this correlation is observed to break down at spatial scales less than a few hundred parsecs (Boulanger and Péroult 1988).

In order to examine the FIR-radio correlation of NGC 3044, we first compared the total FIR fluxes and the radio continuum data. The 20-cm D-array, naturally weighted map has a large beam size ($55''$). The total flux from this map is 106 ± 3 mJy

(Sorathia, 1994). This is comparable with the peak flux density of 114 ± 30 mJy obtained from the single-dish Green Bank telescope at 1.4 GHz (White and Becker, 1992 and Condon and Broderick, 1985). The single-dish flux is the total flux since the galaxy is not resolved in the beam, therefore we believe that the D-array data have detected the total flux at 1.465 GHz (20-cm). Together with the flux densities at 60 and $100\mu\text{m}$, the single beam ratio of FIR to radio flux densities, following Helou *et al.* (1985), is

$$q = \log[FIR/(3.75 \times 10^{12} \text{Hz})]/S_{20\text{-cm}} = 2.18 \pm 0.03. \quad (3.25)$$

This value agrees with $\langle q \rangle = 2.3 \pm 0.2$ obtained from the various galaxy samples (Helou *et al.* , 1985) .

To find the ratio of FIR to radio fluxes *within* NGC 3044, the $60\mu\text{m}$ map is convolved to the $100\mu\text{m}$ beam and a map of FIR is formed. The 20-cm map is also convolved to the $100\mu\text{m}$ beam before taking the ratio. The result is a map of q values with mean of 2.27 ± 1.43 (s.d.) (Figure 3.27). Due to the large beam size, as represented by the size of the cross on the contour map, only a general trend in q is justifiable from Figure 3.27. q peaks near the radio continuum peak and falls off almost uniformly out to about $90''$. The rms noise of the map is estimated from the rms noise of the two maps used for the ratio and is given by 0.01 in log. Therefore, the variation seen in the contour map is significant. This decreasing trend is consistent with that seen in other galaxies (e.g., Bica and Helou 1990, Fitt *et al.* 1992). The position of the HI high latitude feature, F10, is labelled in Figure 3.27. It can be seen that the values of q in this region follow the smooth decline as the rest of the galaxy, that is, it is not anomalous. Note, however, that this could be due to the low resolution.

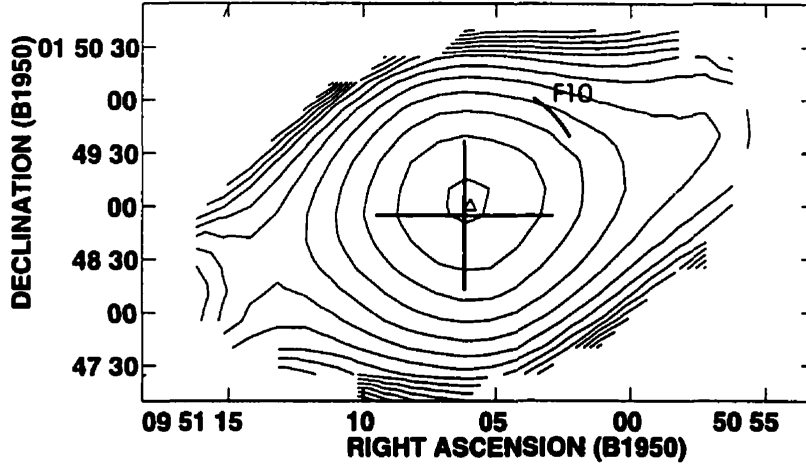


Figure 3.27: FIR-to-Radio Continuum Ratio in NGC 3044

Contours of the FIR/Radio ratio in the log, q , showing the centrally peaked nature of the ratio. Δ represents the radio continuum peak and $+$ represents the IRAS position as well as the size of the $100\mu\text{m}$ beam. Contour are from 1.80 to 2.50 at 0.05 intervals. The HI high latitude spur, Feature 10, is indicated for reference.

A negative gradient of q with respect to distance from the nucleus is understood as due to the smaller scale length of the far-infrared disk compared to that of the radio disk. The diffusion length of a relativistic cosmic ray electron before significant energy lost occurs is typically of order kpc (Bicay *et al.* 1989; Bicay and Helou 1990) while the optical depth of ultraviolet photons from massive young stars (which are responsible for heating the dust that emits the infrared radiation) is much smaller (of order hundreds of parsecs). The far-infrared emission farther in the disk probably arises from colder dust heated by the ambient radiation field dominated by intermediate-mass (hence older) stars. This component of the far-infrared emission is likely to be cooler which explains the lower q values further out in the disk.

The fact that the global FIR/radio ratio, as well as the distribution of the ratio within the galaxy, conform to the correlation seen in normal spiral galaxies indicates that the coupling between the thermal and the non-thermal components in this galaxy

is not anomalous. That is, according to the current understanding of this correlation, the star formation rate and the cosmic ray production rate and diffusion processes in the galaxy is regulated by a common mechanism which is also active in other galaxies. This has an important implication in terms of understanding whether supershell galaxies as a group display any anomalous characteristics, especially in their star formation activities.

3.9 Summary

In this chapter, we have presented results of various observations of NGC 3044. We have shown that the neutral gas is asymmetrically distributed in a moderately thick disk (scale height of 560 pc) with major axis of 34 kpc. Many high-latitude HI features were found and are discussed in detail in Chapter 5. The molecular gas distribution is traced using the ^{12}CO J=2 $\rightarrow$ 1 emission line. This component is found to be centrally peaked with an integrated intensity distribution showing an enhancement on the NW side. A line ratio analysis indicates two types of clouds near the nucleus, one high-density, thermally excited and optically thick, the other low-density and optically thin. The latter type of clouds may be identified with the envelopes of Galactic dark clouds. The radio continuum emission was previously found to be distributed in a thick disk and an extensive radio halo with semi-minor axis of about 8 kpc in projection (Sorathia 1994). Far-infrared data, however, shows that the galaxy is only mildly starbursting with IR luminosity slightly less than $10^{10} L_{\odot}$, the rather arbitrary dividing line between starburst and non-starburst galaxies. This galaxy conforms to the global FIR-radio correlation found in spiral galaxies, as well as the centrally-peaked FIR-radio ratio distribution within the galaxy, indicating that the

relationship between star formation and cosmic ray propagation is no different than other galaxies. The asymmetric distribution in this galaxy is not limited to the neutral gas. In fact, we find that the optical, radio continuum, $H\alpha$ and maybe even the molecular gas distributions also show global asymmetry. In the optical and in HI, the receding (SE) side of the galaxy is more extended while in the radio continuum and in $H\alpha$ the approaching (NW) side is more extended. The asymmetry in NGC 3044 is discussed in detail in Chapter 6.

Chapter 4

NGC 5775

4.1 Introduction

NGC 5775 is a barred spiral within a small group of galaxies (group 148, Geller and Huchra 1983) in the Virgo-Libra Cloud (Tully, 1988). It is classified as infrared-bright in Soifer *et al.* (1987) and a starburst galaxy in Condon and Broderick (1988). The optical parameters of this galaxy, obtained from the RC3, are listed in Table 4.1. Its high inclination [85°8, Irwin 1994] makes it favourable for studying any high-latitude features it hosts. On the POSS print (Figure 4.1), NGC 5775 has a nearby face-on companion, NGC 5774; but both galaxies appear morphologically undisturbed on POSS prints. This leads Solomon and Sage (1988) to classify NGC 5775 as a Type I galaxy (see §3.1). Irwin (1994) presented detailed analysis of the HI distribution in NGC 5775 and NGC 5774. In this study, two HI bridges connecting the two galaxies were reported, hence firmly establishing that they interact. In addition, various high-latitude arcs and extensions were discovered in NGC 5775. Hummel *et al.* (1991) found a thick radio continuum disk with an exponential scale height of 950 pc (at a distance of 24.8 Mpc, which is used throughout this work, see §4.2.4). Note that $1'' \equiv 0.12$ kpc at this distance ($H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is adopted here).

More recently, Sorathia (1994) reported the existence of a radio continuum halo in NGC 5775, amongst other edge-on galaxies. The FWHM at the 2σ contour is 12

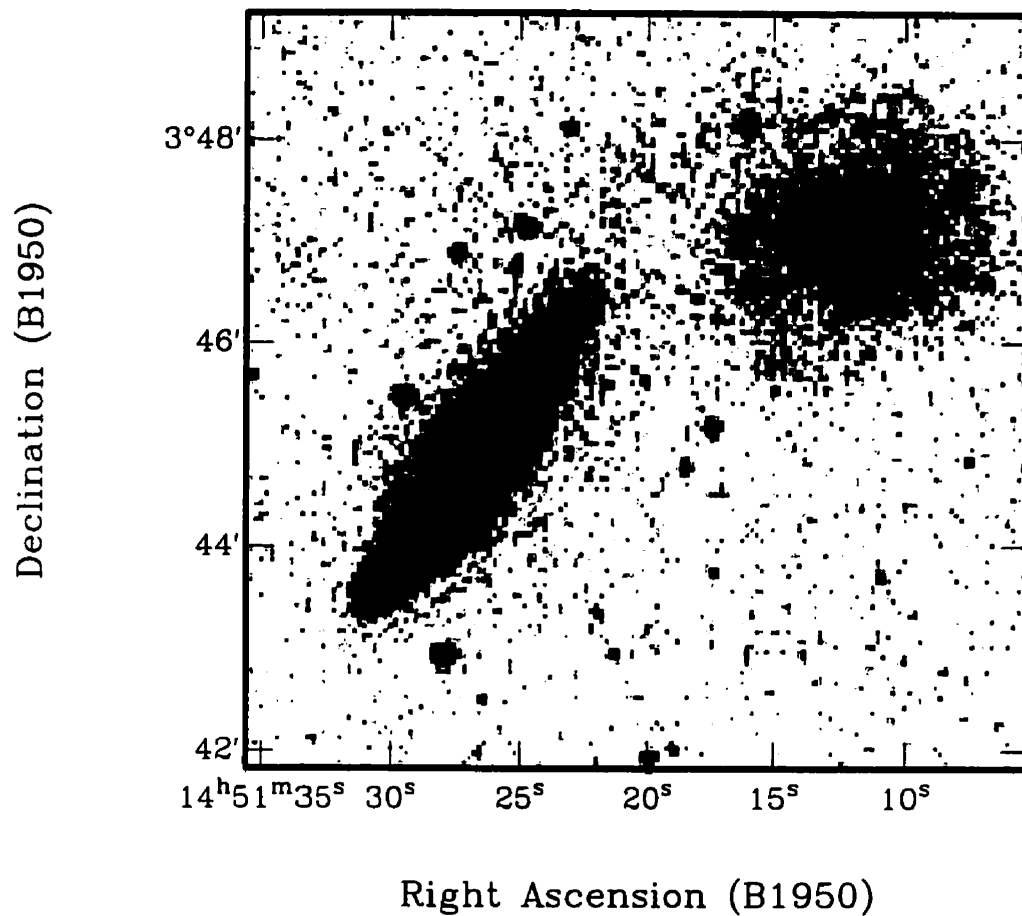


Figure 4.1: Optical Image of NGC 5775

Digital Sky Survey image of NGC 5775, the edge-on spiral on the left. NGC 5774 is the face-on companion to its northwest. IC 1070 (a dwarf companion) on the southwest of NGC 5775 is not shown.

Table 4.1: Basics Parameters of NGC 5775^a

Morphological Type	SBC?sp ^b
$\alpha(1950)$	14 ^h 51 ^m 26 ^s .8
$\delta(1950)$	3°44'51"0
Major $\times$ Minor axis ^c	4'.2 $\times$ 1'.0
Heliocentric Velocity	1681 km s ⁻¹
Blue Magnitude	12.24

^a From the RC3.^b The ? refers to a "Doubtful" classification^c Measured at the 25th magnitude level.

to 15 kpc (corrected for beam smearing). Duric *et al.* (1997), using VLA B, C and D array combined data (hence achieving higher sensitivity as well as higher resolution compared to Sorathia's data), study in detail the radio continuum halo of NGC 5775. They also confirm a radio halo extending up to 10 to 15 kpc above and below the plane (see Figure 4.17), with an exponential scale height from 2.8 to 4.7 kpc. They argue for a 2-component radio brightness distribution consisting of the halo surrounding and permeating a radio continuum disk. The disk can be fit with a Gaussian with sigma of 0.7 to 1.4 kpc (beam deconvolved), which agrees with the results of Hummel (1991). The radio continuum disk and halo are characterized by spectral indices of 0.6 and 1.0, respectively. The steeper spectral index of the halo is attributed to the diffusion and energy losses of cosmic ray electrons. The disk spectrum can be accounted for by a superposition of discrete sources and the diffuse steep-spectrum component. A radio continuum bridge connecting NGC 5775 and NGC 5774 is detected and it coincides with the southern bridge found in the HI.

The organization of this chapter is as follows. For completeness, we summarize the HI results of Irwin (1994) in §4.2. The carbon monoxide emission results are

reported in § 4.3. The radio continuum maps were kindly supplied by Duric *et al.* (1997) for the purpose of comparing radio continuum distributions with data in the other wavebands. We present these maps in § 4.4. High-resolution infrared (HIRES) maps and an H α image kindly supplied by R.-J. Dettmar will be presented in § 4.5 and § 4.6, respectively. In § 4.7, we present correlations of these different wavebands and finally in § 4.8 we give a summary of the chapter.

4.2 The HI Distribution in NGC 5775

This section summarizes the results of the detailed study of the HI distribution in NGC 5775 by Irwin (1994). All figures and tables in this section have been adapted from Irwin (1994).

4.2.1 The HI Channel Maps

The observing parameters for NGC 5775 are listed in Table 2.1. The naturally weighted velocity channel maps of NGC 5775 are reproduced in Figure 4.2. The SE side of the galaxy is receding and the NW side is approaching. Various arcs and extensions away from the disk of the galaxy can be seen in these maps. For example, at the velocity 1767 km s^{-1} , two features can be seen, one at $\alpha = 14^{\text{h}}51^{\text{m}}30^{\text{s}}$, $\delta = 3^{\circ}44'36''$, and the other at $\alpha = 14^{\text{h}}51^{\text{m}}26^{\text{s}}.8$, $\delta = 3^{\circ}43'51''$. At 1642 km s^{-1} , another can be seen at $\alpha = 14^{\text{h}}51^{\text{m}}27^{\text{s}}$, $\delta = 3^{\circ}46'0''$. These features are shown more clearly in the column density map presented in the next section. A detailed analysis of these features is deferred to Chapter 5. The northern and southern bridges connecting the two galaxies are especially prominent at velocity 1558 km s^{-1} , indicating a gas transfer is underway between them. Irwin (1994), using a velocity argument,

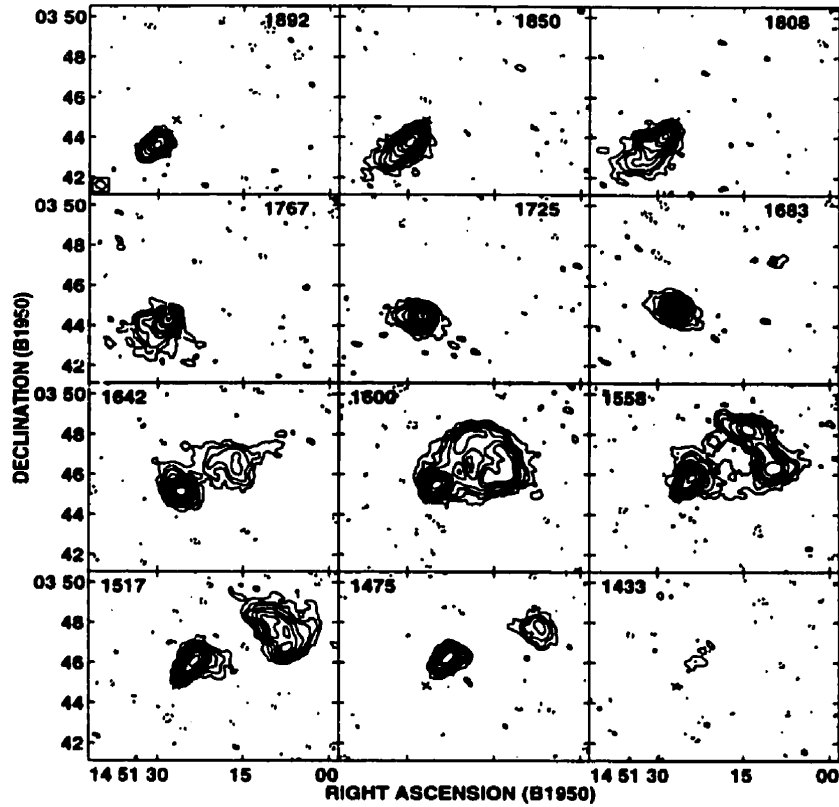


Figure 4.2: Naturally Weighted Velocity Channel Maps of NGC 5775

Contour levels are at $-0.94, 0.94(2.5\sigma), 2, 3, 5, 7.5, 10, 15, 20, 28, 37$ mJy/beam. The channel width is 42 km s^{-1} centred at the velocity which appears at the upper left or right corner of each frame (in km s^{-1}). The synthesized beam is shown at the lower left corner of the first frame.

suggests that gas is being transferred from NGC 5774 to NGC 5775.

4.2.2 The Column Density Maps

The uniformly weighted column density map is superimposed on the optical image in Figure 4.3. The column density map shows NGC 5775 to have a straight disk (except

near the SE tip where it bends towards the NE). The total length of the HI disk is 5.3 (or $1.3 \times R_{25}$) measured at the lowest contour level. A central HI depression similar to the central HI hole in the Milky Way Galaxy is found in this galaxy. On the NW major axis, two column density peaks are found with the outer peak being stronger and offsets about 10.3 kpc from the galaxy's nucleus. A single peak can be seen on the SE major axis. High-latitude extensions can also be identified in the column density map. Good examples are features located at $\alpha = 14^{\text{h}}51^{\text{m}}29^{\text{s}}.6$, $\delta = 3^{\circ}44'36''$ (Feature 1 or F1), $\alpha = 14^{\text{h}}51^{\text{m}}26^{\text{s}}.8$, $\delta = 3^{\circ}43'51''$ (Feature 2 or F2), and $\alpha = 14^{\text{h}}51^{\text{m}}27^{\text{s}}.7$, $\delta = 3^{\circ}46'00''$ (Feature 3 or F3). These features resemble loops or shells with the most extended of them reaching as high as 7 kpc above the midplane in projection.

4.2.3 The Velocity Field

The velocity field of NGC 5775 (Figure 4.4) is typical of a disk galaxy in differential rotation. As in NGC 3044, the kinematic major and minor axes are not perpendicular to each other indicative of a bar structure which is consistent with its morphological classification. The velocity contours display kinks and bends in them suggesting gas being shocked by the spiral arms.

4.2.4 The HI Global Profile

In Table 4.2, we list the global HI properties of NGC 5775 given in Irwin (1994). Despite interacting with NGC 5774, NGC 5775 (and NGC 5774, not listed) has global parameters which agree with values typical for isolated galaxies in its morphological class.

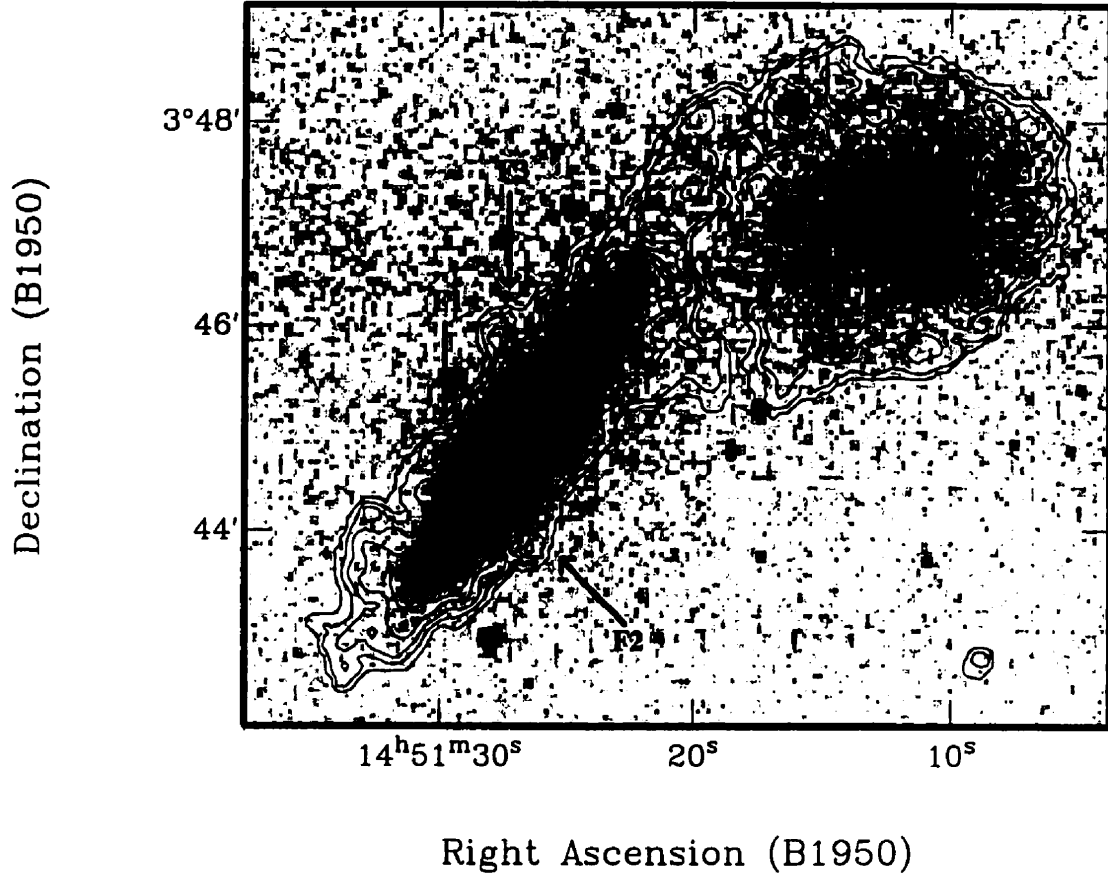


Figure 4.3: The Uniform Weighting Column Density Map of NGC 5775
 The map is superimposed on the optical Digital Sky-Survey image (Fig. 4.1). Hanning smoothing is applied in velocity space using 5 channels and spatially using a Gaussian of FWHM=16". A cutoff of $|0.5| \text{ mJy beam}^{-1}$ is applied. Contour levels are at 1, 5, 10, 17.5, 25, 40, 60, 82.5, and $110 \times 10^{20} \text{ cm}^{-2}$. The high-latitude features are labelled as F1, F2 and F3, although F3 looks more like an open-topped shell.

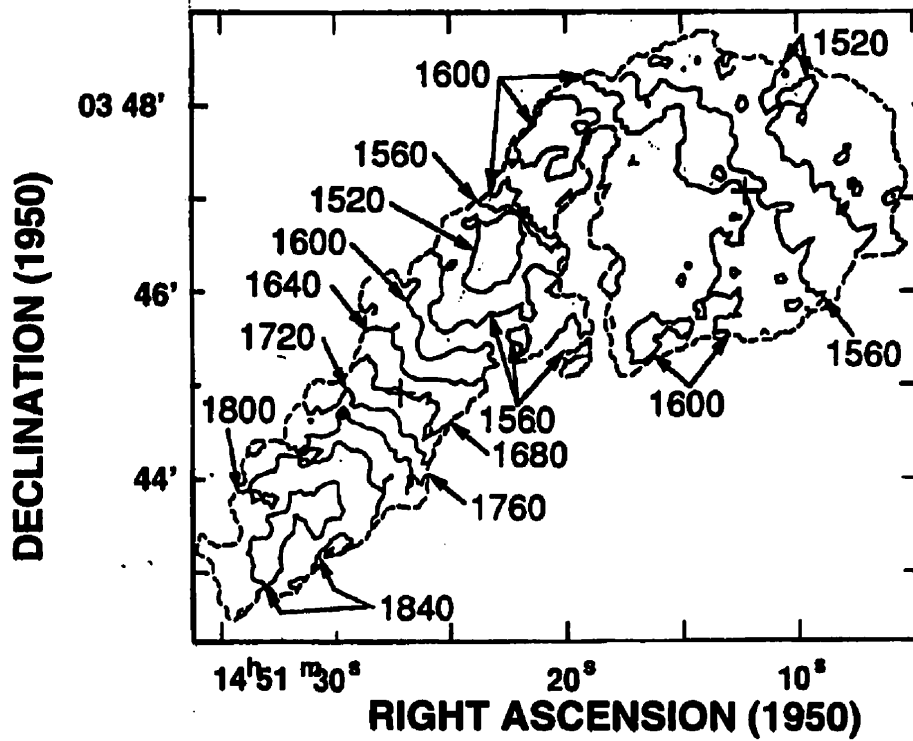


Figure 4.4: The Uniform Weighting Velocity Field of NGC 5775
Intensity-weighted mean velocity field obtained as described in the figure caption of Figure 4.3. Contours in km s^{-1} are labelled with arrows. The crosses indicate the nuclei of NGC 5775 and NGC 5774.

Table 4.2: Global HI Properties of NGC 5775

Parameter	Value
V_{sys}	$1681 \pm 10 \text{ km s}^{-1}$
D_{Hubble}	24.8 Mpc^a
$\Delta V_{20\%}$	$463 \pm 10 \text{ km s}^{-1}$
$\int S \cdot dV$	$63.4 \pm 4.5 \text{ Jy} \cdot \text{km s}^{-1}$
M_{HI}	$(9.1 \pm 0.6) \times 10^9 M_{\odot}$
M_{HI}/L_B	$0.32 \pm 0.02 M_{\odot}/L_{\odot}$
M_T	$(1.5 \pm 0.2) \times 10^{11} M_{\odot}$
M_T/L_B	$5.3 \pm 0.7 M_{\odot}/L_{\odot}$
M_{HI}/M_T	0.06 ± 0.01

^aThe distance derived from the Tully-Fisher relation (following Bottinelli *et al.* (1984)) is given by 18.0 Mpc

4.2.5 Data Cube Modeling and Results

NGC 5775 was modeled using the method described in § 3.3.5. The best-fit model is a ring with a Gaussian distribution in the plane and an exponential distribution in the vertical direction [RG(GS)-EX]. In Table 4.3, we list the best-fit results when modeling NGC 5775 as a whole. Modeling the receding and approaching sides separately did not improve the fit, suggesting that the gas distribution is symmetrical, at least within the spread of parameters within the galaxy as a whole.

Galaxy's Geometry

The geometrical parameters, $\alpha_o(1950)$, $\delta_o(1950)$, PA and i are very well constrained and agree with the optical determination.

Table 4.3: Model Parameters for NGC 5775

Model Parameter	Whole Galaxy RG(GS)-EX
$\alpha_o(1950)$	$14^h51^m26^s.71 \pm 0^s.04$
$\delta_o(1950)$	$3^\circ44'51'' \pm 1''$
PA($^\circ$)	145.9 ± 0.4
$i(^\circ)$	85.8 ± 0.4
$V_{sys}(\text{km s}^{-1})$	1681.1 ± 0.2
$V_{max}(\text{km s}^{-1})$	198 ± 3
$R_{max}(kpc)$	10.8 ± 0.1
$R_o(kpc)$	11.4 ± 0.1
m	1.3 ± 0.1
$n_{max}(cm^{-3})$	0.187 ± 0.008
$r_o(kpc)$	5.5 ± 0.1
$z_o(kpc)$	1.100 ± 0.004
$r_i(kpc)$	7.2 ± 0.1
$\sigma_v(\text{km s}^{-1})$	24 ± 1

The Rotation Curve

The form of the rotation curve in Table 4.3 is the Brandt curve with index $m = 1.3$ (see §3.3.5). However, the goodness of the fit is not sensitive to the form of the rotation curve. The systemic velocity agrees with that given in the RC3. The maximum rotation velocity (198 km s^{-1}) occurs at about three quarters of the way to the edge of the optical disk (i.e., $0.75R_{25}$) and at about half the radius of the HI disk. No significant deviations from a regularly rotating galaxy were observed. The inclusion of a line-of-sight velocity dispersion in the models improved the fit significantly, and the best model has a velocity dispersion of 24 km s^{-1} .

The Density Distributions

The best-fit density distribution has a ring centered at the outer column density peak on the NW major axis and is also near the location of the peak rotation velocity (R_{max}). Irwin (1994) pointed out that this is also the position where the northern and southern bridges between the two galaxies will meet in the disk if extrapolated from the column density map. She therefore suggests that the stronger column density peak on the NW major axis is the result of the gas inflow from NGC 5774. The maximum volume density given by the model (0.187 cm^{-3}) is lower than in both the Milky Way Galaxy and M31. However, significant local deviations from a smooth distribution are also observed. The vertical gas distribution is represented by an exponential law with a scale height of 1.1 kpc. This scale height is large compared to the corresponding parameter of the Milky Way (see Chapter 1), and is similar to the thick radio continuum disk found by Hummel *et al.* (1991) and Duric *et al.* (1997).

4.3 The CO Distribution in NGC 5775

We observed NGC 5775 in the various CO rotational transitions in order to study the molecular gas distribution. The observing details and data reduction procedures are presented in Chapter 2 and Table 2.2 and 2.4. In summary, we obtained, from the JCMT, ^{12}CO $J=2\rightarrow1$, ^{13}CO $J=2\rightarrow1$, and ^{12}CO $J=3\rightarrow2$ spectra. The ^{12}CO $J=1\rightarrow0$ spectra were obtained from the SEST by G. Golla and were generously given to us. The ^{12}CO $J=1\rightarrow0$ and ^{12}CO $J=2\rightarrow1$ emission of NGC 5775 were mapped to large distances (15.6 kpc in radius) in order to obtain the molecular gas distribution in the disk. The ^{12}CO $J=3\rightarrow2$, ^{13}CO $J=2\rightarrow1$ and ^{13}CO $J=3\rightarrow2$ emission were observed near the galaxy's nucleus. For the purposes of line ratio analysis in the direction of the galaxy's nucleus, we fully sampled the area within the large ($43''$) beam of the SEST with the ^{12}CO $J=2\rightarrow1$ ($21''$) beam of the JCMT. Similarly, the area within the ^{12}CO $J=2\rightarrow1$ beam was fully sampled by the $14''$ ^{12}CO $J=3\rightarrow2$ beam. In the following, we present the CO results of these data.

4.3.1 The Spectra

Figures 4.5, 4.6, 4.7, 4.8 and 4.9 show the individual spectra in the ^{12}CO $J=1\rightarrow0$ emission, the inner and outer region in the ^{12}CO $J=2\rightarrow1$ emission, and in the ^{12}CO $J=3\rightarrow2$ emission, respectively. Figure 4.10 displays the single spectrum of the ^{13}CO $J=3\rightarrow2$ line at the position offset of $(-12, 0)$ from the galaxy's nucleus. Figure 4.11 shows the spectra at or close to the nucleus for each transition.

From Figure 4.5, we can see that the molecular disk of the galaxy is receding on the SE side (lines are red-shifted) and approaching on the NW side (lines at blue-shifted), as in the HI disk. The molecular gas distribution is centrally peaked, in contrast to

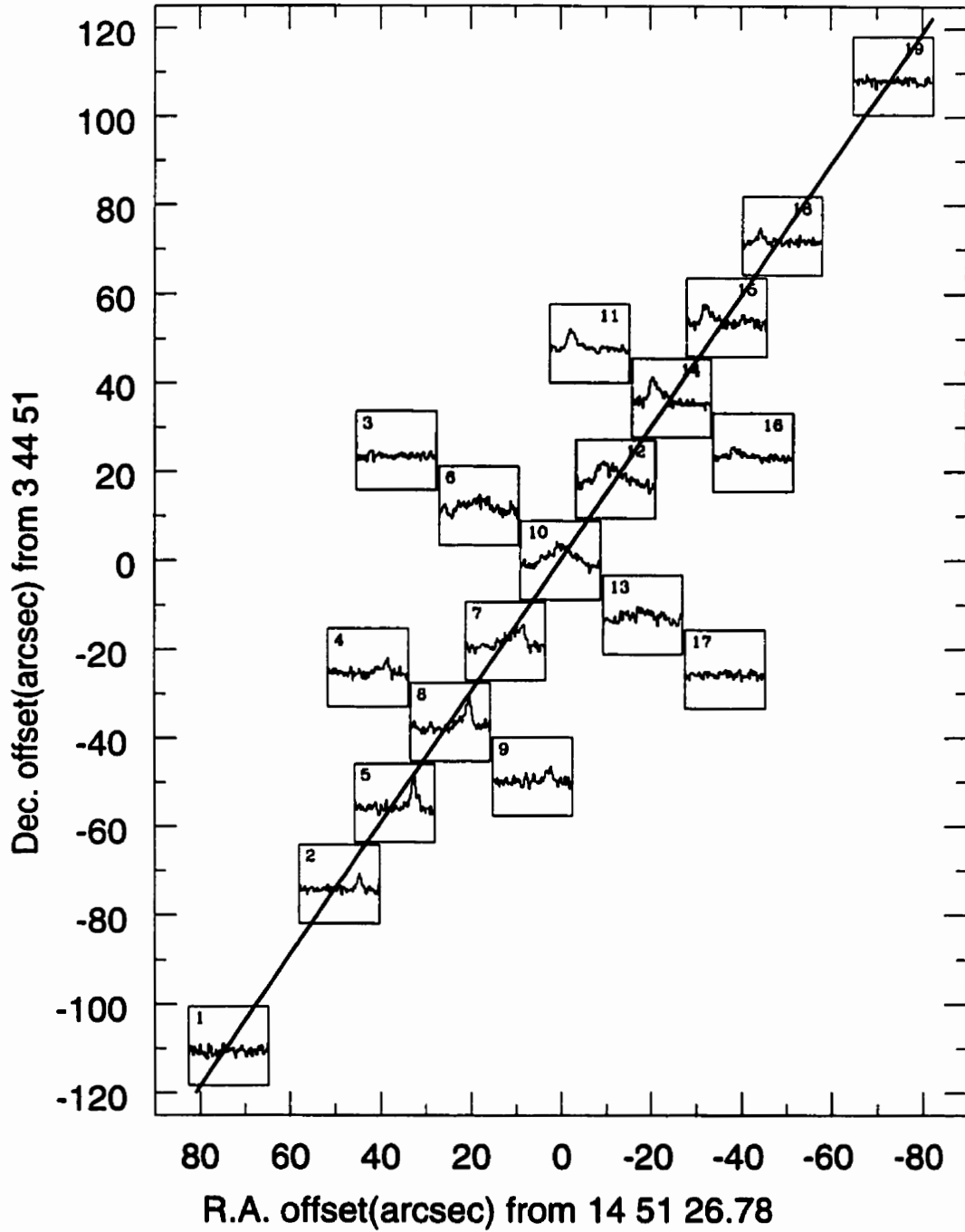


Figure 4.5: Individual ^{12}CO $J=1\rightarrow 0$ spectra of NGC 5775. Each spectrum shown has LSR velocity from 1350 to 2000 km s^{-1} on the horizontal axis and main beam temperature (T_{MB}) from -0.15 to 0.20 K on the vertical axis. The line across the page represents the optical major axis. The HPBW is $43''$.

the HI which has a central depression. This kind of distribution is commonly seen in other spiral galaxies. Along the major axis, emission can be traced out to $\pm 90''$ (about 11 kpc radius) judging from spectra 2 and 18. The ^{12}CO J=2 $\rightarrow$ 1 map shows essentially the same distribution in the disk (see Figure 4.6). ^{12}CO J=3 $\rightarrow$ 2 emission is detected at all observed positions except at the offset (-22.4, 2.0), and ^{13}CO J=2 $\rightarrow$ 1 emission (see bottom panel in Figure 4.11) is detected at the nucleus. Unfortunately, ^{13}CO J=3 $\rightarrow$ 2 was only observed at the offset (-12, 0) and only yields an upper limit (Figure 4.10).

In Figure 4.11, four spectra on or near the galaxy's nucleus each of a different CO transition (with different beam size) are displayed. The line shapes of these spectra are similar. Take for example the ^{12}CO J=2 $\rightarrow$ 1 spectrum, in which there appears to be three components superimposed. The peak is at about 1680 km s^{-1} , and two "shoulders", one on each side of the peak, emitted by gas at high red- and blue-shifted velocities can be seen from 1800 km s^{-1} to 1880 km s^{-1} and 1480 km s^{-1} to 1580 km s^{-1} , respectively. The ^{12}CO J=1 $\rightarrow$ 0 spectrum also shows these peaks while the ^{13}CO J=2 $\rightarrow$ 1 spectrum shows only the blue-shifted shoulder. This could be because the redshifted peak is lower and may be lost in the noise of the ^{13}CO J=2 $\rightarrow$ 1 spectrum. The ^{13}CO J=2 $\rightarrow$ 1 to ^{12}CO J=2 $\rightarrow$ 1 ratio (see §4.3.5 below) is 0.09, we therefore expect the peak of the red-shifted wing to be 2.5 mK, which is below the noise level (3 mK) of this spectrum. The ^{12}CO J=3 $\rightarrow$ 2 spectrum has a much narrower profile although there are signs of the spectrum flattening at about 1600 km s^{-1} on the blue side and at 1750 km s^{-1} on the red side. This again may be attributed to the lower S/N of this spectrum. Using a non-linear least squares routine (XGAUS in AIPS), the ^{12}CO J=1 $\rightarrow$ 0 and the ^{12}CO J=2 $\rightarrow$ 1 spectra can each be fitted by three Gaussian components. These Gaussian components are listed in

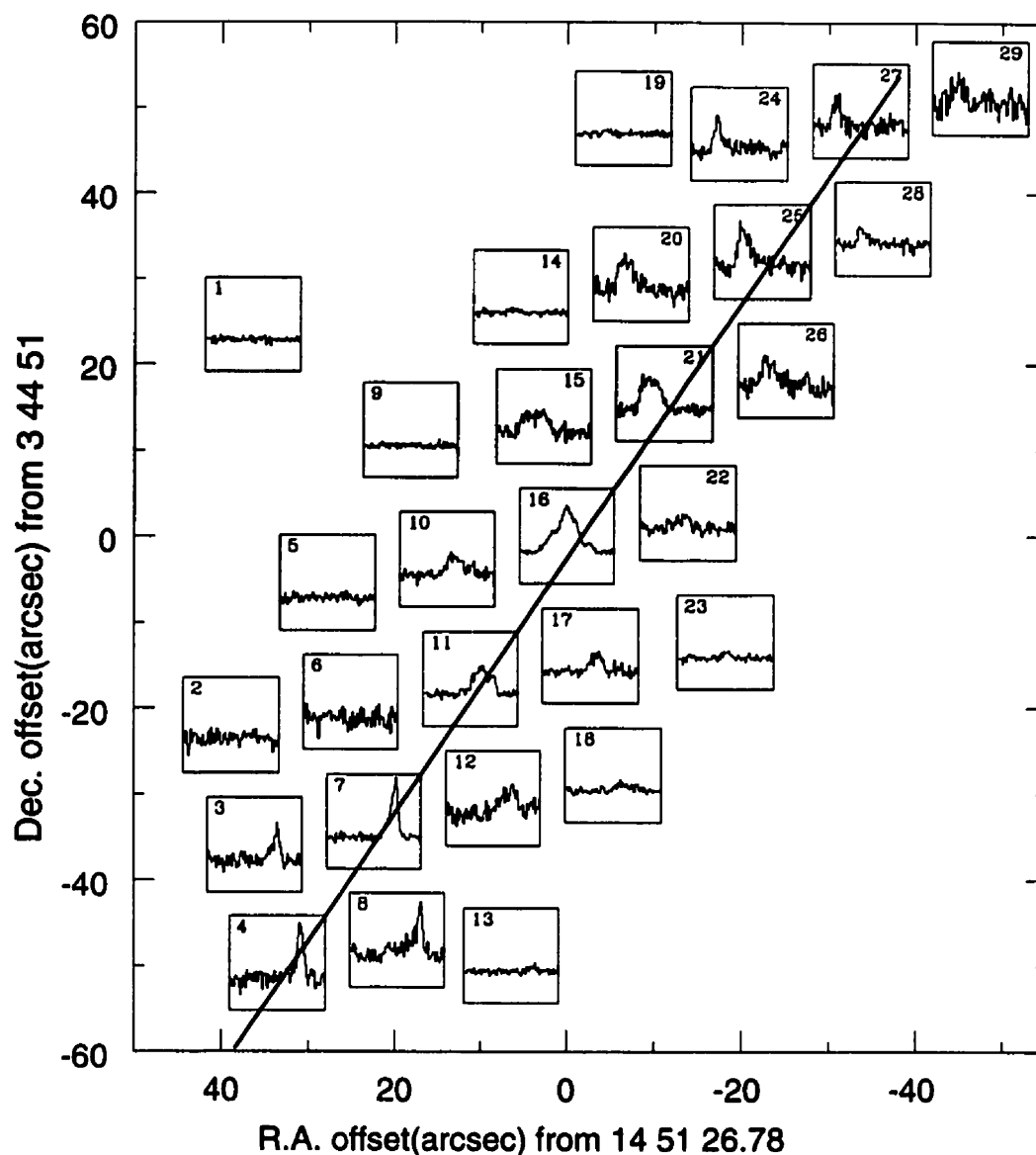


Figure 4.6: Individual ^{12}CO $J=2\rightarrow 1$ spectra of the Inner Region of NGC 5775. Spectra at the inner $40''$ by $40''$ region of NGC 5775. Each spectrum shown has LSR velocity from 1350 to 2000 km s^{-1} on the horizontal axis and T_{MB} from -0.15 to 0.30 K on the vertical axis. Three other spectra with offset positions close to spectra 9, 22 and 23 are shown separately (in Figure 4.7) in order not to clutter this diagram. The line across the page represents the optical major axis. The HPBW for this transition is $21''$.

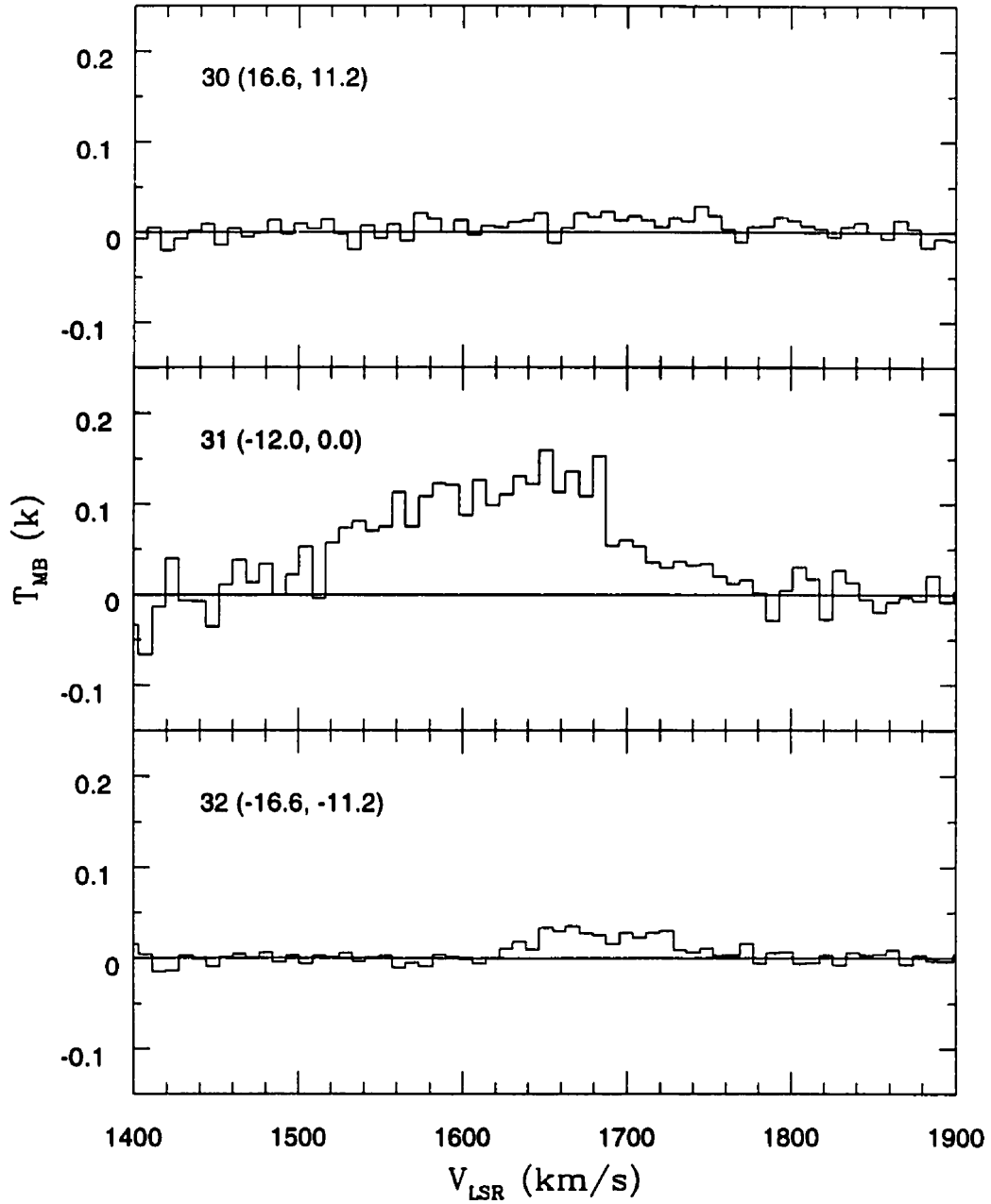


Figure 4.7: More ^{12}CO J=2→1 Spectra in the Inner Region of NGC 5775. Three spectra in the inner region of NGC 5775 that are not shown in Figure 4.6. Spectrum number and position offset are shown on the upper left of each panel.

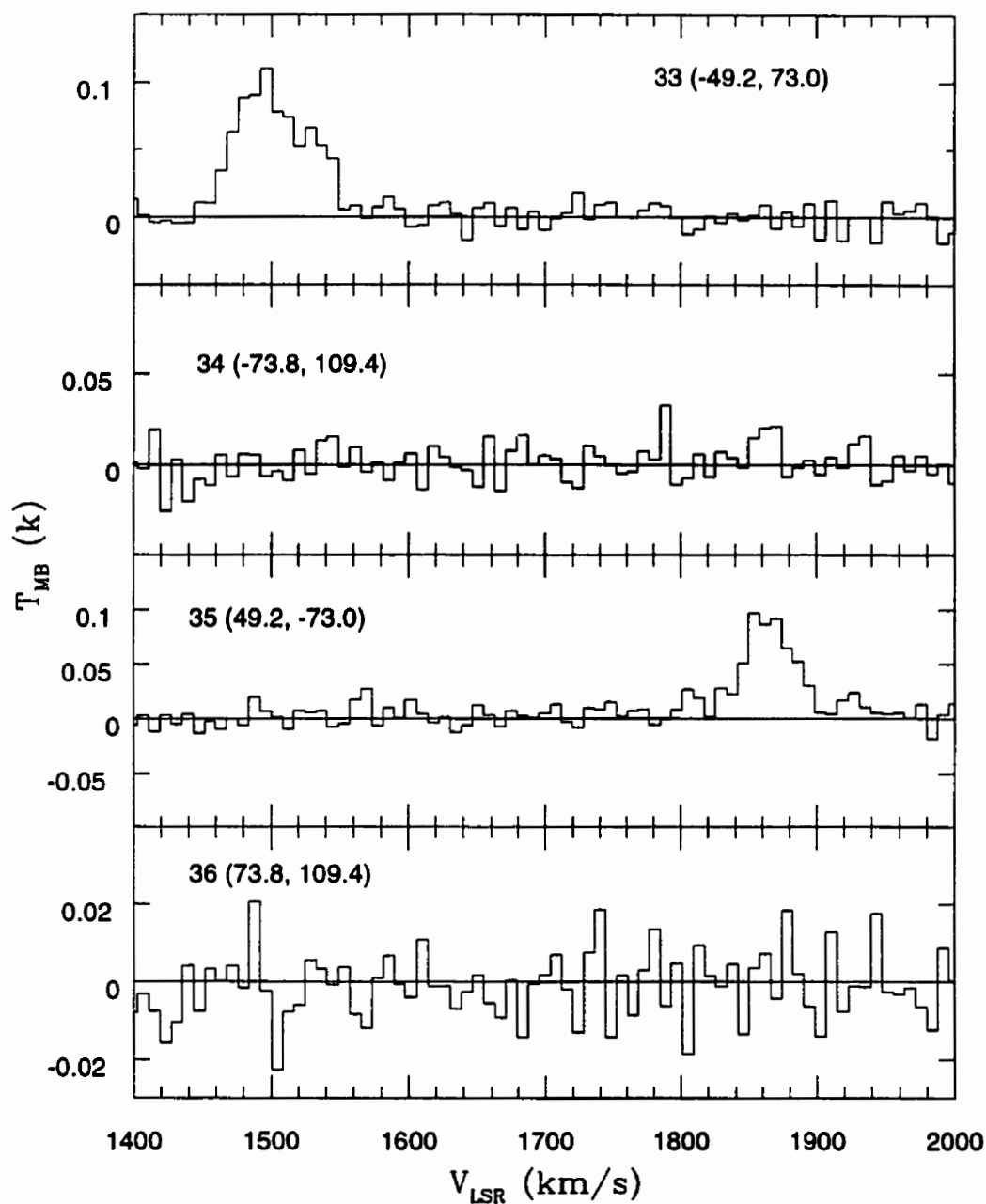


Figure 4.8: ^{12}CO $J=2\rightarrow 1$ spectra of the Outer Region of NGC 5775. Spectra at the outer region of NGC 5775. All four spectra are on the major axis of the galaxy. The top two spectra are on the NW side and the bottom two are on the SE side. Spectrum number and position offset are shown on the upper left or right of each panel.

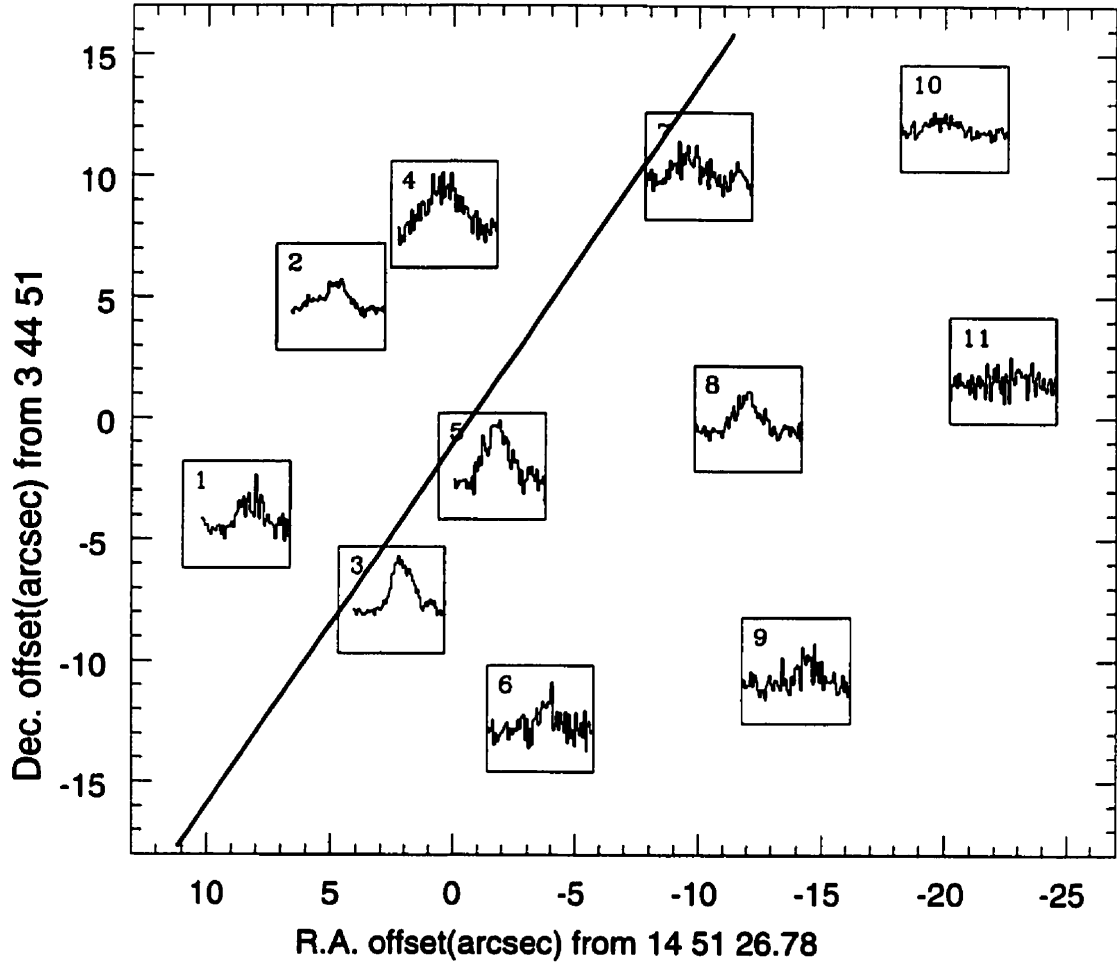


Figure 4.9: Individual ^{12}CO $J=3\rightarrow 2$ spectra of NGC 5775. Each spectrum shown has LSR velocity from 1400 to 1900 km s^{-1} on the horizontal axis and T_{MB} from -0.15 to 0.25 K on the vertical axis. The line across the page represents the optical major axis. The HPBW for this transition is $14''$.

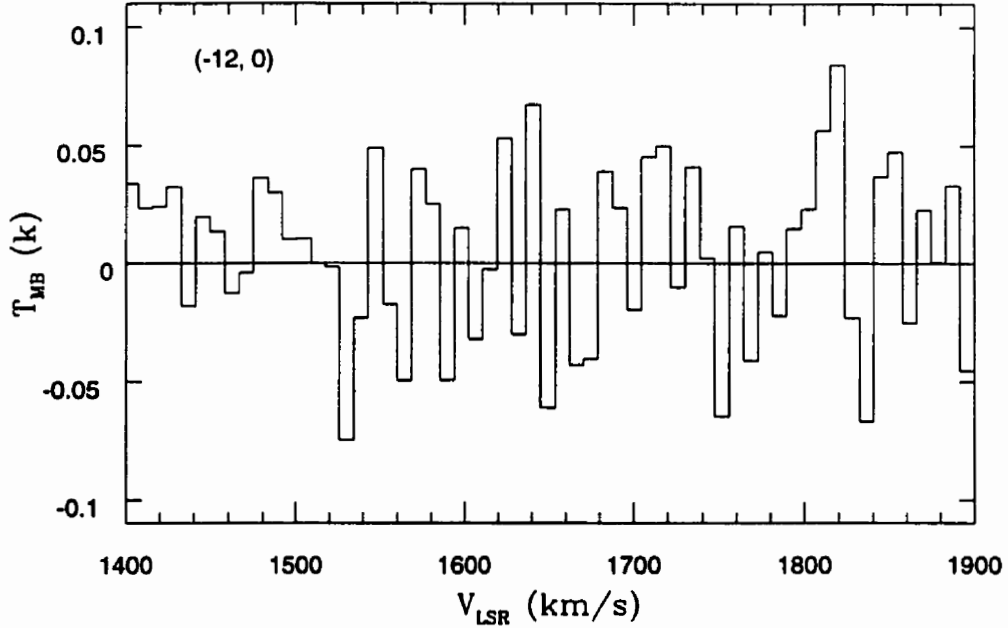


Figure 4.10: ^{13}CO $J=3\rightarrow 2$ spectrum of NGC 5775. The ^{13}CO $J=3\rightarrow 2$ spectrum at position offset $(-12, 0)$.

Table 4.4. The peak velocities of the central Gaussian component for both spectra agree with the systemic velocity of the galaxy obtained with the HI data. The peak velocities of the blue-shifted components in the ^{12}CO $J=1\rightarrow 0$ and the ^{12}CO $J=2\rightarrow 1$ spectra do not agree with each other but the red-shifted components do.

The observations in the previous paragraph have two implications. First, the similar line shapes of the different transitions means that the emission probably arises from similar regions in the galaxy. Second, the high-velocity wings in the spectra indicate that some gas in the central regions is moving with higher line-of-sight (l-o-s) velocity, both toward and away from the observer. We tentatively refer to these high velocity wings as the nuclear disk since such disks are seen in the Milky Way Galaxy (Dame *et al.* 1987) as well as in other galaxies (e.g., NGC 891, García-Burillo *et al.* 1992). A single Gaussian that peaks at the systemic velocity (i.e., the central

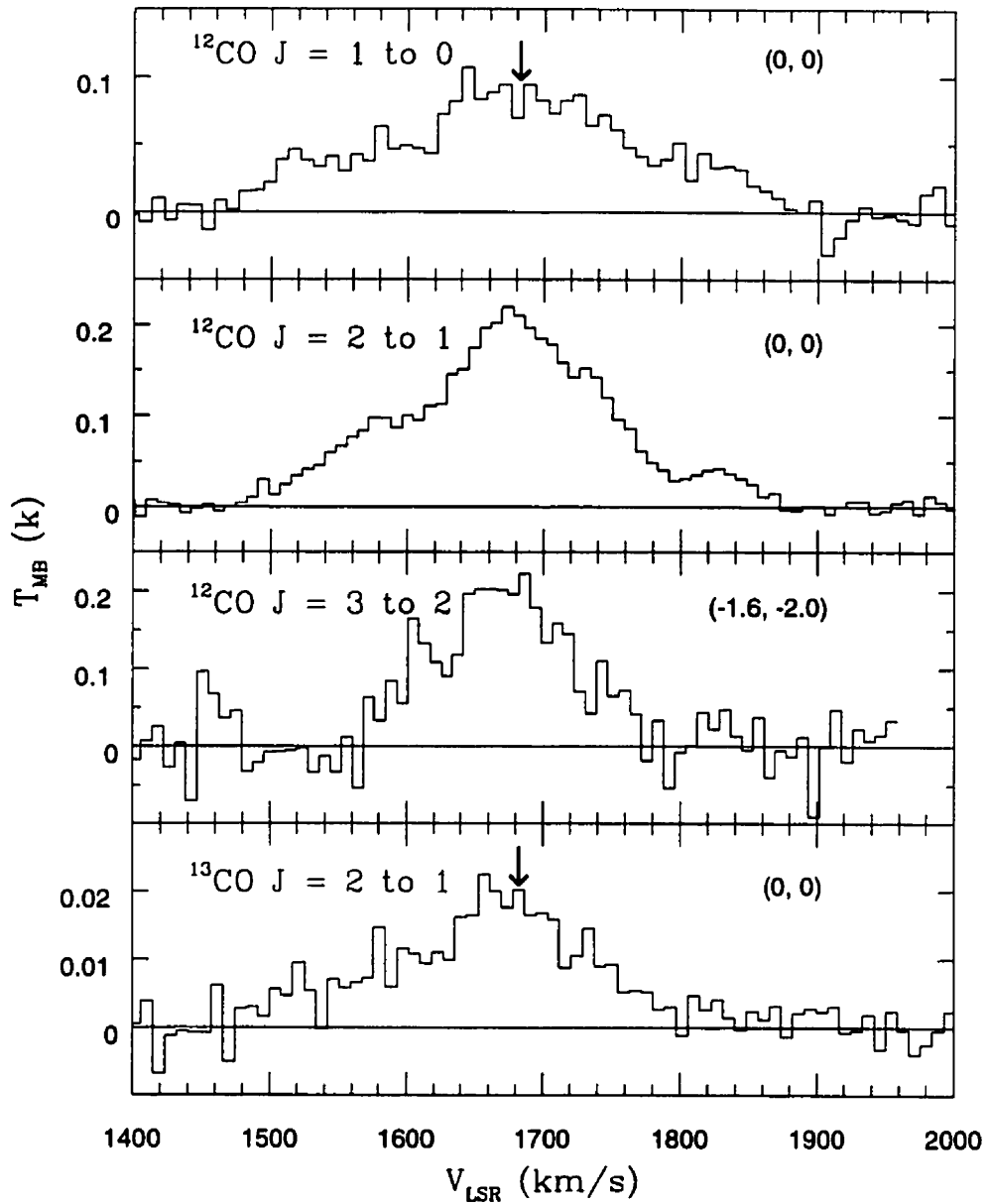


Figure 4.11: Nuclear CO Emission in NGC 5775

The $^{12}\text{CO } J=1 \rightarrow 0$ (top panel, HPBW=43"), $^{12}\text{CO } J=2 \rightarrow 1$ (second panel, HPBW=21") and $^{13}\text{CO } J=2 \rightarrow 1$ (bottom panel, HPBW=21") spectra at the nucleus of NGC 5775 [(0, 0)]. The third panel shows the $^{12}\text{CO } J=3 \rightarrow 2$ (HPBW=14") spectrum closest to the nucleus, at offset (-1.6, -2.0), for comparison. The downward arrows indicated the systemic velocity at 1681 km s^{-1} .

Table 4.4: Gaussian Components of the ^{12}CO J=1 $\rightarrow$ 0 and the ^{12}CO J=2 $\rightarrow$ 1 Nuclear Spectra of NGC 5775

Gaussian Parameters	^{12}CO J=1 $\rightarrow$ 0			^{12}CO J=2 $\rightarrow$ 1		
Amplitude (K)	0.090 (0.010) ^a	0.023 (0.010)	0.029 (0.010)	0.203 (0.006)	0.034 (0.006)	0.058 (0.006)
FWHM (km s ⁻¹)	178 (16)	57 (21)	64 (18)	135 (4)	77 (7)	43 (8)
Peak Velocity (km s ⁻¹)	1678 (4)	1828 (8)	1522 (7)	1683 (2)	1832 (3)	1558 (3)

^aValues in brackets are associated uncertainties of the fits.

For Amplitudes, the uncertainties are the rms noise of the spectra since they are larger than the formal 1σ uncertainties given by the fitting routine.

peaks of the spectra in Figure 4.11) would be expected if the nuclear region is a simple solid-body rotating disk, in which case the velocity width of the spectrum would be the velocity dispersion of the clouds along the l-o-s plus the effect of the disk inclination and the disk thickness. The relative velocity of the peak of the red-shifted component is 150 km s⁻¹ with respect to the systemic velocity. The peak of the blue-shifted component has relative velocity of 156 km s⁻¹ in ^{12}CO J=1 $\rightarrow$ 0 and 125 km s⁻¹ in ^{12}CO J=2 $\rightarrow$ 1. Since the high velocity wings are not seen in the ^{12}CO J=2 $\rightarrow$ 1 spectra one beamwidth (21" or 2.5 kpc) away on either side along the major axis (spectra 11 and 21 in Figure 4.6), we conclude that the diameter of the nuclear disk is ≤ 2.5 kpc. The total integrated intensity from the ^{12}CO J=1 $\rightarrow$ 0 spectrum is 1.98 K-km s⁻¹ for the blue wing and 1.39 K-km s⁻¹ for the red wing. The total molecular gas mass in the nuclear disk is then given by $6.3 \times 10^8 M_{\odot}$

(equation 3.18). If we assume for a moment that such a rapidly rotating disk resides in the central 1.2 kpc radius of the galaxy at a rotation velocity of 150 km s^{-1} , we estimate its dynamical mass to be $6.3 \times 10^9 M_{\odot}$ (equation 3.6), making the molecular mass contribution 10% of the dynamical mass within this radius.

4.3.2 The Nature of the Inner CO High Velocity Gas

The two high-velocity peaks may be interpreted as a high-velocity rotating disk near the galaxy's nucleus such as those seen in some galaxies, e.g. NGC 4631 (Sofue *et al.* 1990), NGC 891 (Sofue and Nakai 1993). If this is indeed a rapidly rotating disk, we would expect the approaching (blue-shifted) and the receding (red-shifted) sides to be symmetrical in terms of relative velocities and intensities. From the fitted Gaussian components we see that this is indeed the case in $^{12}\text{CO } J=1 \rightarrow 0$, with relative velocities ($\sim 150 \text{ km s}^{-1}$) and peak intensities ($\sim 26 \text{ mK}$) of the two sides agreeing within the uncertainties. However, it is not true in $^{12}\text{CO } J=2 \rightarrow 1$. There may be differences in excitation conditions between the approaching and the receding side. The $^{12}\text{CO } J=2 \rightarrow 1$ to $^{12}\text{CO } J=1 \rightarrow 0$ ratio of the receding side is less than that of the approaching side indicating that the rapidly rotating disk is optically thin and that the excitation temperature on the receding side is lower. From the LVG modeling (see below), we know that the clouds in the central region are at least not optically thick, although some lines have moderate optical depth. However, the bulk of the emission for the line ratio analysis comes from the normal disk gas (the central peaks in the $^{12}\text{CO } J=1 \rightarrow 0$ and $^{12}\text{CO } J=2 \rightarrow 1$ spectra in Figure 4.11). Current data do not have the resolution to probe the excitation conditions in the nuclear disk.

Another possible interpretation of the high velocity components is that they represent an outflow such as that seen in the starburst galaxy M82 (Nakai *et al.* 1987, Shen

and Lo 1995), or in NGC 3628 (Irwin and Sofue 1996). If $6.3 \times 10^8 M_{\odot}$ of molecular gas is being ejected from the nucleus at a velocity of about 150 km s^{-1} , the kinetic energy ($\frac{1}{2} M_{\text{gas}} V_{\text{gas}}$) of the gas is 1.4×10^{56} ergs. Can the starburst in NGC 5775 provide this energy? The massive star formation rate (SFR) in the central 1.2 kpc radius is estimated using the relation between the massive SFR and the nonthermal luminosity within this radius given by Condon (1992),

$$\left(\frac{L_N}{\text{erg s}^{-1} \text{ Hz}^{-1}} \right) \sim 5.3 \times 10^{47} \left(\frac{\nu}{\text{GHz}} \right)^{-\alpha} \left(\frac{\text{SFR}}{M_{\odot} \text{ yr}^{-1}} \right), \quad (4.1)$$

where L_N is the nonthermal luminosity, ν is the observed frequency, and α is the nonthermal spectral index. From the 20 cm radio continuum data of similar beam size supplied by Duric *et al.* (1997) (see §4.4), we found L_N at the central 1.2 kpc radius to be $2.55 \times 10^{47} \text{ erg s}^{-1} \text{ Hz}^{-1}$. At the nucleus of the galaxy, the spectral index given in Duric *et al.* (1997) is 0.72. These then give a SFR of $0.64 M_{\odot} \text{ yr}^{-1}$. The radio supernova rate (number of supernova per year) is related to the SFR by $0.041 \times \text{SFR}$ (Condon 1992) and gives 0.03 SN/yr. If we assume this rate to be constant over the lifetime of one generation of massive stars ($\sim 5 \times 10^7 \text{ yr}$) and that each supernova releases 10^{51} ergs of energy, 10% of which gets converted into kinetic energy, then over $5 \times 10^7 \text{ yr}$, the total kinetic energy released is 1.5×10^{56} ergs. Therefore, the starburst activity in NGC 5775 is just enough to drive a molecular outflow based on the energetics.

With currently available data, we can not distinguish the nature of the high-velocity gas seen at the central 1.2 kpc radius of NGC 5775. It may be a fast rotating disk or a molecular outflow. The CO integrated intensity contours at high latitude along the minor axis hint at molecular gas out of the plane. If high latitude CO is detected in the future, then the outflow scenario may be proven. Additionally,

high-resolution interferometric observations will help to verify the existence of a fast rotating disk.

4.3.3 Position-Velocity Diagram

The ^{12}CO $J=1\rightarrow 0$ p-v diagram is presented in Figure 4.12, superimposed on the HI rotation curve for comparison. Based on the 3σ CO contour (third lowest contour), the maximum rotation velocity is 206 km s^{-1} on the approaching side (NW) and 175 km s^{-1} on the receding side (SE), with an uncertainty in velocity of $\pm 9 \text{ km s}^{-1}$. The HI PV diagram shows a maximum rotation velocity of 250 km s^{-1} with the two sides agreeing within the velocity uncertainty $\pm 20 \text{ km s}^{-1}$. The difference in maximum rotation velocities obtained from the CO and the HI data can entirely be accounted for by the velocity resolutions and the velocity dispersion of the HI gas (FWHM = 56 km s^{-1} , Irwin 1994, which will be higher than that of the molecular gas). The high velocity gas in the nuclear disk discussed above is not obvious in the p-v diagram. This is unlike the CO rotation curve of NGC 891 (Sofue and Nakai 1993) which shows the rapidly rotating disk at the nucleus clearly as two spikes in velocity space. The spatial resolution in that study is much better than here though. The “clump” on the flat part of the curve on the SE side ($50''$, 1830 km s^{-1}) corresponds to the turnover in the HI rotation curve. The dynamical mass within a 12 kpc ($100''$) radius inferred from the CO data is found to be $1.0 \pm 0.2 \times 10^{11} M_{\odot}$ assuming spherical geometry (from the third contour). The uncertainty quoted is half the difference between the mass calculated using the approaching and the receding maximum rotation velocities. The dynamical mass within the inner 2.6 kpc radius is $1.8 \pm 0.3 \times 10^{10} M_{\odot}$. These masses both agree with that inferred from the HI p-v diagram when the velocity resolution and HI gas velocity dispersion are taken into account.

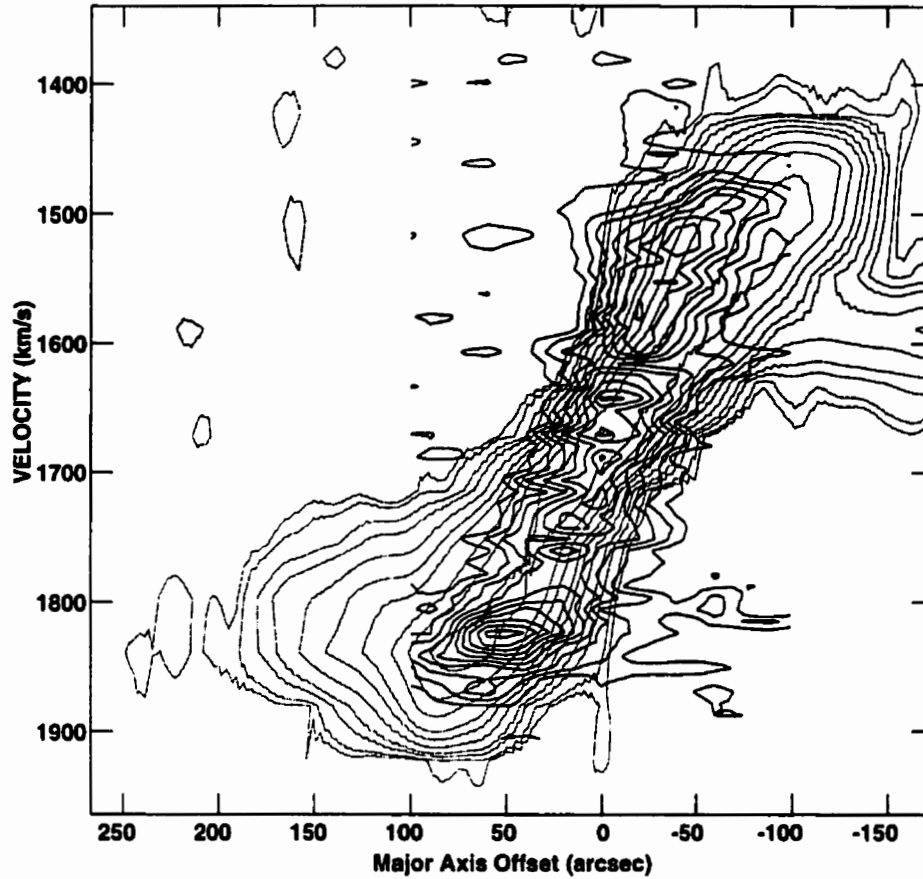


Figure 4.12: The ^{12}CO $J=1\rightarrow 0$ Major Axis Position-Velocity Diagram of NGC 5775. The ^{12}CO $J=1\rightarrow 0$ rotation curve (black contours) is superimposed on the HI rotation curve (natural weighting data, grey contours). The CO contour levels are at 1.3 (1σ), 2.6, 3.9, 5.2, 6.5, 7.8, 9.1, 10.4, 11.7, and 13.0×10^{-2} K. The HI contour levels are at 0.56 (1.5σ), 0.94, 2, 3, 5, 7.5, 10, 15, 20, 28 and 37 mJy/beam. The two data sets are not smoothed to the same resolutions. The systemic velocity is 1681 km s^{-1} .

4.3.4 Integrated Intensity

Integrated intensities are obtained for each spectrum and are listed in Table 4.5. The uncertainty in each integrated intensity is 20%. The maps of integrated intensity for the ^{12}CO J=1 $\rightarrow$ 0 and the ^{12}CO J=2 $\rightarrow$ 1 transitions are presented in Figure 4.13 and 4.14. Despite the different beamwidths, the distributions of the two maps are very similar, both being centrally peaked and with inner contours which are more extended to the SE along the major axis. Both maps show a narrowing in the contours at $\alpha = 14^{\text{h}}51^{\text{m}}28^{\text{s}}, \delta = 3^{\circ}44'36''$. At $\alpha = 14^{\text{h}}51^{\text{m}}31^{\text{s}}, \delta = 3^{\circ}43'50''$ in the ^{12}CO J=1 $\rightarrow$ 0 map, there appears to be a small peak which is not seen in the ^{12}CO J=2 $\rightarrow$ 1 map. As it is near the edge of the observed field, the reality of it is questionable. Figure 4.15 displays a slice of the ^{12}CO J=1 $\rightarrow$ 0 integrated intensities along the major axis of NGC 5775. The thickness of the slice is $40''$ ($\sim$ HPBW). This plot shows that the integrated intensity decreases by 50% within about $40''$ (4.8 kpc) of the nucleus.

Table 4.5: Integrated Intensities of NGC 5775

Offset		Peak	RMS	S/N	Velocity Interval	Integrated	Spectrum ^a
		Intensity	Noise			Intensity	Number
(arcsecs)		(mK)	(mK)		(km s^{-1})	(K-km s^{-1})	
^{12}CO J=1 $\rightarrow$ 0							
0.0	0.0	61	10	6.1	1480 1900	20.4	10
24.6	-36.5	89	14	6.4	1685 1890	9.8	8
-24.6	36.5	80	10	8.0	1340 1735	13.3	14
36.5	24.6	...	11	...	No Detection		3

continued on next page

Offset		Peak	RMS	S/N	Velocity Interval	Integrated	Spectrum ^a
		Intensity	Noise			Intensity	Number
(arcsecs)		(mK)	(mK)		(km s ⁻¹)	(K-km s ⁻¹)	
2.7	13.9	91	22	4.1	1484 1751	16.3	15
13.9	-2.7	87	17	5.1	1621 1865	12.7	10
-2.7	-13.9	76	17	4.5	1628 1784	7.0	17
-13.9	2.7	56	16	2.5	1528 1757	7.5	22
16.6	11.2	17	11	1.5	1571 1822	2.6	30
27.8	-5.4	30	14	2.1	1651 1835	1.9	5
25.1	-19.3	...	31	...	No Detection		6
-12.0	0.0	127	32	4.0	1453 1778	22.7	31
22.4	-33.2	255	12	21.3	1710 1898	17.4	7
5.4	27.8	19	8	2.4	1574 1687	1.4	14
-16.6	-11.2	32	8	4.0	1622 1801	3.0	32
-5.4	-27.8	34	9	3.8	1640 1898	4.8	18
-8.5	30.5	134	29	4.6	1502 1705	17.9	20
-22.4	33.2	184	27	6.8	1455 1705	20.1	25
-25.1	19.3	122	30	4.1	1420 1689	14.9	26
8.5	-30.5	123	29	4.2	1658 2030	20.7	12
19.7	-47.0	238	23	10.3	1568 1893	21.3	8
33.6	-49.7	241	24	10.0	1698 1878	14.7	4
36.2	-35.9	145	22	6.6	1730 1867	8.6	3

continued on next page

Offset	Peak	RMS	S/N	Velocity	Interval	Integrated	Spectrum ^a
	Intensity	Noise				Intensity	Number
(arcsecs)	(mK)	(mK)		(km s ⁻¹)		(K-km s ⁻¹)	
38.9 -22.0	28	26	1.1	1742	1957	4.3	2
-19.7 47.0	153	25	6.1	1477	1625	8.8	24
-33.6 49.7	138	27	5.1	1466	1577	8.3	27
-36.2 35.9	72	19	3.8	1486	1648	6.4	28
-47.4 52.4	103	47	2.2	1460	1592	9.2	29
18.2 12.3	...	9	...	No Detection			9
36.5 24.6	...	11	...	No Detection			1
-6.4 48.8	16	10	1.6	1463	1629	1.4	19
49.2 -73.0	87	12	7.3	1793	1962	5.3	35
73.8 -109.4	...	9	...	No Detection			36
-73.8 109.4	...	9	...	No Detection			34
-49.2 73.0	96	10	9.6	1443	1597	6.6	33
-18.2 -12.3	28	11	2.5	1630	1737	1.9	23
6.4 -48.8	20	12	1.7	1777	1866	1.4	13
¹³ CO J=2→1							
0.0 0.0	20	3	6.7	1478	1870	3.3	
¹² CO J=3→2							
-12.0 0.0	138	18	7.7	1541	1755	17.4	8
-1.6 -2.0	194	35	5.5	1571	1787	25.2	5

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Offset		Peak	RMS	S/N	Velocity Interval	Integrated	Spectrum ^a
		Intensity	Noise			Intensity	Number
(arcsecs)		(mK)	(mK)		(km s ⁻¹)	(K-km s ⁻¹)	
-3.6	-12.4	142	44	3.2	1610 1770	10.9	6
8.8	-4.0	119	32	3.7	1612 1825	13.3	1
0.4	8.4	142	33	4.3	1472 1822	28.5	4
-10.0	10.4	89	33	2.7	1495 1722	12.3	7
-20.4	12.4	44	19	2.3	1491 1690	6.7	10
-14.0	-10.4	94	29	3.2	1629 1830	10.8	9
-22.4	2.0	...	37	...	No Detection		11
5.0	5.0	94	10	9.4	1513 1773	14.1	2
2.5	-7.5	194	8	24.3	1574 1858	25.7	3
¹³ CO J=2→1							
-12.0	0.0	...	37	...	No Detection		

^aThe spectrum numbers coincide with the spectrum numbers in Figures 4.5, 4.6, 4.7, 4.8 and 4.9.

The total column density and molecular gas mass within the 43'' (2.6 kpc in radius) ¹²CO J=1→0 beam are $6.1 \times 10^{21} \text{ cm}^{-2}$ and $3.8 \times 10^9 M_{\odot}$, respectively (from equations 3.17 and 3.18), with an uncertainty of roughly a factor of 2 as discussed in §3.4.5. This includes the nuclear disk mass of $6.3 \times 10^8 M_{\odot}$ and is 14% of the dynamical mass within the same region. We have also obtained the HI mass within this region by smoothing the HI naturally weighted data to the beamwidth of the ¹²CO J=1→0 observation and finding the total integrated flux within this beam. We

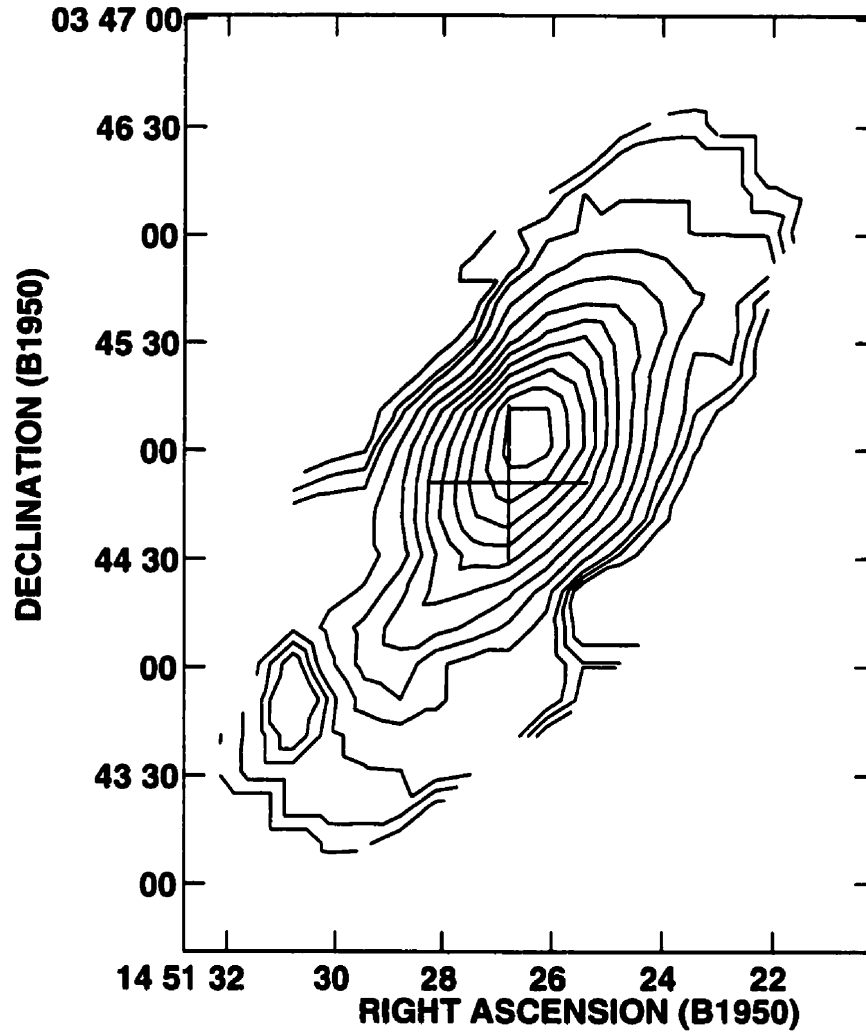


Figure 4.13: Map of the ^{12}CO J=1→0 Integrated Intensity of NGC 5775. Contour levels are at 1, 2, 3, 5, 7, 9, 11, 13, 15, 17, 19 and 21 K km s^{-1} . The cross marks the centre of the galaxy and the size of the beam.

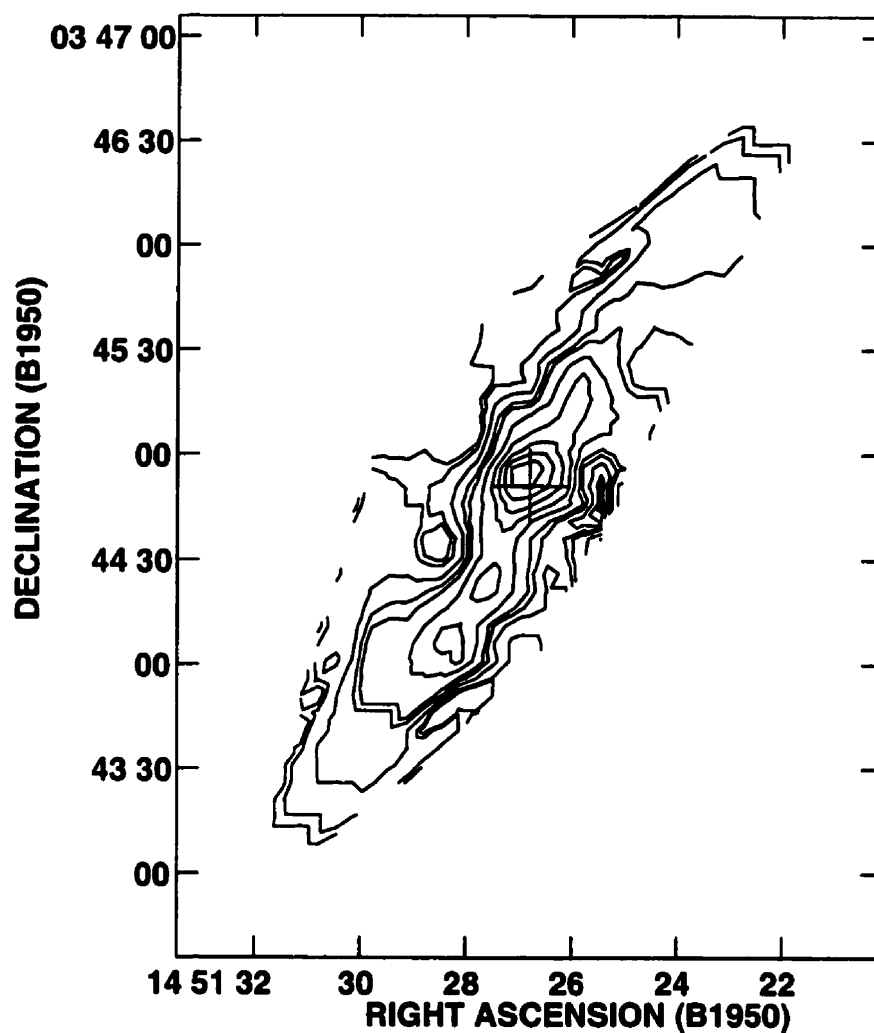


Figure 4.14: Map of the ^{12}CO J=2→1 Integrated Intensity of NGC 5775. Contour levels are at 1, 2, 5, 8, 10, 15, 20, 25, 30, 35 K-km s^{-1} . The cross marks the centre of the galaxy and the size of the beam.

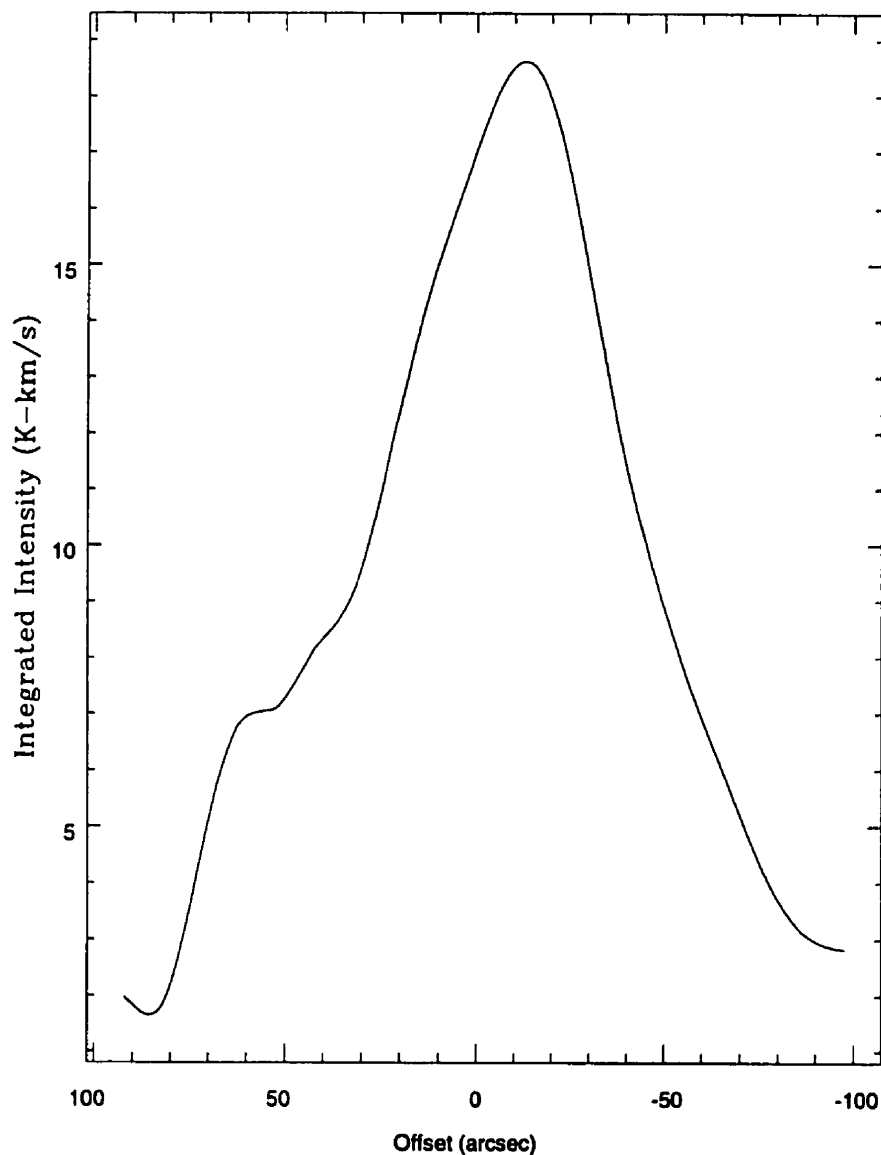


Figure 4.15: Distribution of the ^{12}CO $J=1\rightarrow 0$ Integrated Intensity Along the Major Axis of NGC 5775.

The position offsets on the horizontal axis are with respect to the nucleus of the galaxy at $\alpha = 14^{\text{h}}51^{\text{m}}26^{\text{s}}.8$, $\delta = 3^{\circ}44'51''$. 20% error is associated with each value.

Table 4.6: Derived Masses of NGC 5775

		12 kpc	2.6 kpc
M_{dyn} (12 kpc Radius) ^a	1.0×10^{11} ^b	$\frac{M(HI)}{M_{H_2}} = 0.53$	0.29
M(HI) (12 kpc Radius)	5.9×10^9	$\frac{M_{H_2}}{M_{dyn}} = 0.11$	0.14
Total M_{H_2} (12 kpc Radius)	1.1×10^{10}	$\frac{M_{gas}}{M_{dyn}} = 0.17$	0.27
M_{dyn} (2.6 kpc Radius)	1.8×10^{10}	$\frac{M_{gas}}{M_{dust}} > 2010$	
Inner M_{H_2} (2.6 kpc Radius)	3.8×10^9		
Inner M(HI) (2.6 kpc Radius)	1.1×10^9		
Nuclear M_{H_2} Disk Mass	6.3×10^8		
Total M(HI) ^c (19 kpc Radius)	9.1×10^9		
Total M_{dust}^d (19 kpc Radius)	1.0×10^7		

^aInferred from ^{12}CO J=1→0 data.^bAll masses in $M_\odot$.^cFrom Irwin (1994).^dDust Mass is derived from the IRAS fluxes in §4.5

find an HI mass of $(1.14 \pm 0.02) \times 10^9 M_\odot$. The total molecular mass within the observed radius of 12 kpc is obtained by summing all the integrated intensities in Figure 4.13 and applying Equation 3.18 which gives $1.1 \times 10^{10} M_\odot$. This represents a lower limit to the molecular gas mass in the galaxy since the outermost region of the galaxy is not mapped. Similarly, we find the HI mass within 12 kpc radius by summing the smoothed data within this region and obtain $(5.9 \pm 0.02) \times 10^9 M_\odot$. Within 12 kpc, the molecular mass makes up 11% of the dynamical mass in the same region. All derived masses and ratios are listed in Table 4.6.

From Table 4.6, we find that gas is dynamically more important in the inner 2.6 kpc region of this galaxy and that the molecular gas is a factor of 2 more concentrated there compared to the larger region. Young and Scoville (1991) show that, globally, the $M_{H_2}/M(\text{HI})$ ratio and the total gas to dynamical mass ratio are both functions of Hubble type, with earlier type galaxies having a larger ratio for $M_{H_2}/M(\text{HI})$ and a smaller total gas to dynamical mass ratio than later type galaxies. For late-type galaxies like NGC 5775 (Sc-type), the statistics in Young and Scoville (1991) show 0.5 and 0.16 as the median $M_{H_2}/M(\text{HI})$ and total gas to dynamical mass ratios, respectively. NGC 5775 fits into the high-end tail of their $M_{H_2}/M(\text{HI})$ distribution and lies near the median of the total gas to dynamical mass distribution. The global gas-to-dust ratio is > 2010 (lower limit because M_{H_2} is itself a lower limit). This value is much larger than the value of ~ 150 used for the Galaxy but is closer to the mean value (~ 1000) found in IRAS galaxies with warm dust (see Young and Scoville 1991 and references therein), consistent with NGC 5775 being a starburst galaxy.

4.3.5 Line Ratio Analysis

We have obtained 4 different line ratios: R_{21} , R_{32} , $^{13}R_{21}$ and $^{13}R_{32}$, each ratio obtained from data smoothed to the larger beam size of the transition in the ratio. The first three values are centred at the nucleus of NGC 5775; $^{13}R_{32}$, however, is offset by $12''$ (1.4 kpc) to the west of the nucleus and is an upper limit since $^{13}\text{CO } J=3 \rightarrow 2$ was not detected. Assuming this line ratio does not change significantly within 1.4 kpc of the galaxy's centre, $^{13}R_{32}$ can be used in the line ratio analysis (see below). In addition, R_{21} is also available along the major axis out to a distance of about $60''$ (7 kpc). The line ratios are listed in Table 4.7 and the map of R_{21} is presented in Figure 4.16. Although NGC 5775 is seen almost edge-on ($i = 85^\circ 8$), the CO beams

Table 4.7: CO Line Ratios in the Direction of the Nucleus of NGC 5775

R_{21}	0.67 ± 0.13 (smoothed to the 43'' beam)
R_{32}	0.55 ± 0.11 (smoothed to the 21'' beam)
$^{13}R_{21}$	0.09 ± 0.02 (21'' beam)
$^{13}R_{32}$ ^a	$\leq 0.09 \pm 0.02$ (14'' beam)

^a This ratio is obtained at the position offset of (-12, 0).

in the direction of the nucleus still probe gas in the central region because the line intensity drops off rapidly (see Figure 4.15) with radius.

Comparing the line ratios in NGC 5775 with those from various similar studies, we find that our values are typical for a late type spiral galaxy. The R_{21} ratio in the direction of the nucleus agrees with the mean of the corresponding ratio of 60 nearby spirals [0.89 ± 0.34 (s.d.), Braine and Combes 1992]; the $^{13}R_{21}$ ratio agrees with that reported by Aalto *et al.* (1995), who gives $^{13}R_{21} < 0.2$ for a sample of predominantly starburst galaxies; the R_{32} ratio is identical to the Galactic value (Sanders *et al.* 1993) and also matches the R_{32} ratio of NGC 3044 to within errors.

Figure 4.16 displays contours of R_{21} superimposed on grey-scale representation of the associated uncertainties. The contour map is obtained by dividing the smoothed (to the ^{12}CO J=1 $\rightarrow$ 0 beam) ^{12}CO J=2 $\rightarrow$ 1 map with the ^{12}CO J=1 $\rightarrow$ 0 map. Both maps were applied a cutoff at 20% of the peaks. The boundary of the contour map should be viewed with caution since the interpolation of individual maps is probably inaccurate at the edges (see §3.4.3 for explanation). Also, beyond about $\pm 60''$ the ^{12}CO J=2 $\rightarrow$ 1 observation does not fully sample the regions inside the ^{12}CO J=1 $\rightarrow$ 0 beam. Therefore we can not interpret the map beyond this radius. From Figure 4.16,

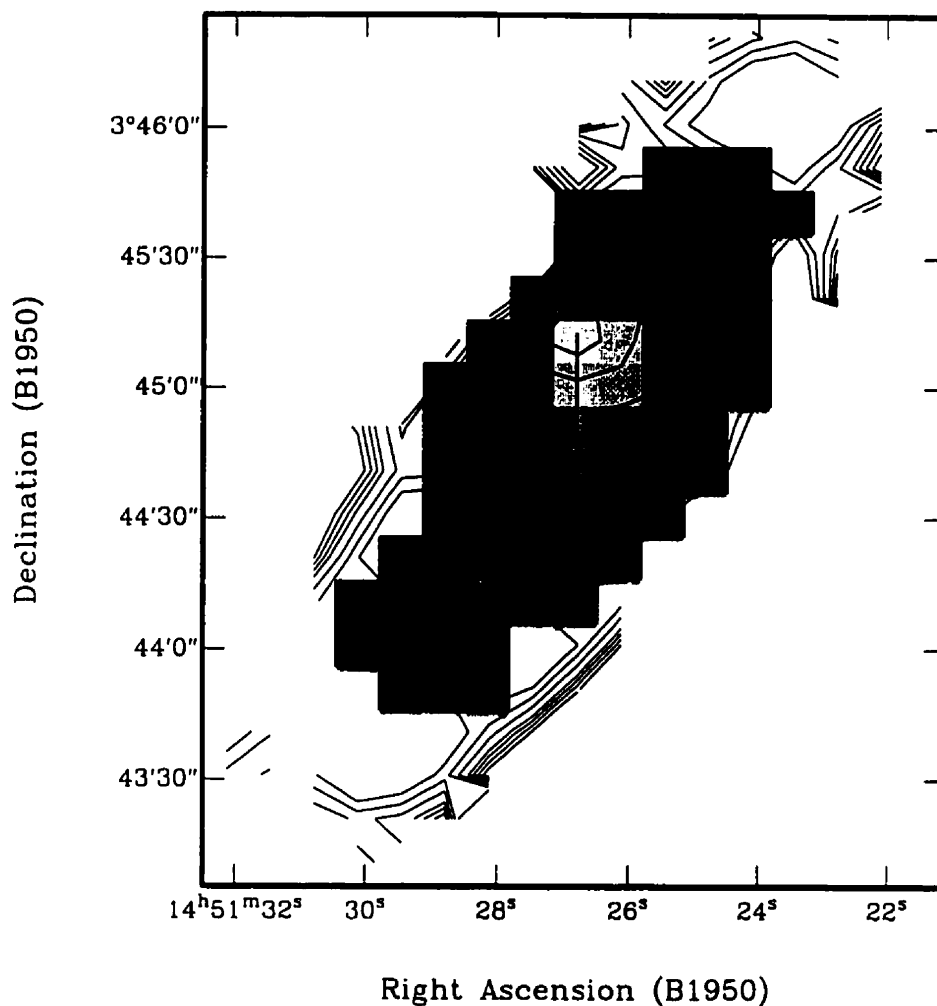


Figure 4.16: Map of R_{21} for NGC 5775.

R_{21} contours superimposed on a grey-scale representation of their associated uncertainties. Contour levels are from 0.55, 0.60, 0.65, 0.70, 0.80, 0.90, 1.00. Grey-scale values range from about 0.2 (lightest) to about 1 (darkest). The cross shows the position of the galaxy's centre and the size represents the 43" beam. The outer region, beyond $\pm 60''$ of the nucleus, should be ignored in this map because the ^{12}CO $J=2\rightarrow 1$ observations did not completely sample the area within the ^{12}CO $J=1\rightarrow 0$ beam.

we detect no spatial variation, above the uncertainties in the map, in R_{21} with galactocentric radius. Flat R_{21} across disks of galaxies are also reported for NGC 891 (García-Burillo *et al.* 1992) and NGC 4631 (Golla and Wielebinski 1994). The flatness of R_{21} with radius suggests that R_{32} may be similarly flat, at least to within the noise. The integrated intensity of the ^{13}CO J=3→2 at the offset position of (12,0) can therefore be compared with that of the ^{12}CO J=3→2 value at the galaxy's nucleus to provide an additional line ratio.

LVG Modeling We model the cloud parameters using the LVG approximation as described in §3.4.4. The one-component LVG code was used with trial $[^{12}\text{CO}]/[^{13}\text{CO}]$ ratios of 25, 50 and 70. Ranges of kinetic temperature (T_K) from 10 to 250 K in steps of 10 K, density (n) from 100 to 10^8 cm^{-3} in steps of $10^{0.5}$, and CO abundance per velocity gradient ($X_{\text{CO}}/(dv/dr)$) from 10^{-10} to $10^{-4} \text{ km s}^{-1} \text{ pc}$ also in steps of half-magnitude were searched for solutions. We find the one-component LVG model was inadequate in describing the physical conditions in the clouds because no solutions were found which could reproduce the observed line ratios within the quoted uncertainties. Since $^{13}R_{32}$ is an upper limit, we also tried values lower by factors of 2, 5, 10 and 20 times, but the conclusion remains. Table 4.8 lists the solution with the lowest χ^2 fit to show that the theoretical line ratios do not all agree with the observed ones listed in Table 4.7. We therefore resort to the two-component LVG model.

The two-component LVG model assumes the radiation received at the telescope are emitted by two types of clouds of different physical properties but originate from the same region in the galaxy (see §3.4.4 for a description of the model). Equation 3.14 “mixes” the radiation temperature of the two types of cloud by means of their relative filling factor (ff). We limit our search of solutions to $^{12}\text{CO}/^{13}\text{CO} = 25$

Table 4.8: Sample One-Component LVG Solutions for NGC 5775

$^{12}\text{CO}/^{13}\text{CO}$	25
T_k (K)	40
n (cm^{-3})	1.0×10^3
$X_{\text{CO}}/(d\nu/d\tau)$ ($\text{km s}^{-1}\text{pc}$)	1.0×10^{-5}
R_{21} (Theoretical)	0.84
R_{32} (Theoretical)	0.59
$^{13}R_{21}$ (Theoretical)	0.096
$^{13}R_{32}$ (Theoretical)	0.054
χ^2 fit	1.74
$T_r(^{12}\text{CO} J = 1 \rightarrow 0)$	15.0
$T_{\text{ex}}(^{12}\text{CO} J = 1 \rightarrow 0)$	22.0
$\tau(^{12}\text{CO} J = 1 \rightarrow 0)$	1.6
$T_r(^{12}\text{CO} J = 2 \rightarrow 1)$	13.0
$T_{\text{ex}}(^{12}\text{CO} J = 2 \rightarrow 1)$	18.0
$\tau(^{12}\text{CO} J = 2 \rightarrow 1)$	5.2
$T_r(^{12}\text{CO} J = 3 \rightarrow 2)$	7.5
$T_{\text{ex}}(^{12}\text{CO} J = 3 \rightarrow 2)$	14.0
$\tau(^{12}\text{CO} J = 3 \rightarrow 2)$	6.3
$T_r(^{13}\text{CO} J = 2 \rightarrow 1)$	1.2
$T_{\text{ex}}(^{13}\text{CO} J = 2 \rightarrow 1)$	7.5
$\tau(^{13}\text{CO} J = 2 \rightarrow 1)$	0.51
$T_r(^{13}\text{CO} J = 3 \rightarrow 2)$	0.40
$T_{\text{ex}}(^{13}\text{CO} J = 3 \rightarrow 2)$	7.9
$\tau(^{13}\text{CO} J = 3 \rightarrow 2)$	0.20

from Table 4.8. The ranges of temperature and ff tried were 15 K to 195 K in steps of 20 K and 1.0×10^{-4} to 1 in half-magnitude steps. The density and abundance ranges were the same as in the one-component case.

As mentioned in §3.4.4, the total number of free parameters (seven) exceeds the number of line ratios (four in this case, with the fourth being the upper limit of $13R_{32}$) resulting in many possible solutions. After some scrutiny, we find that in all solutions, the density of component A does not exceed $1.0 \times 10^4 \text{ cm}^{-3}$, and so there is always a component of clouds that is of low density. There exist solutions in which temperatures and abundances of the two components are the same (i.e., in such solutions, temperature of A = temperature of B AND abundance of A = abundance of B). However, no solutions exist where abundances and densities for the two components are the same, nor are there solutions in which the temperatures and densities of the two components are the same. This may be the reason for the failure of the one-component LVG fitting using all data.

In Table 4.9, we list the solution with the lowest χ^2 value (best-fit) as Model 1. In Model 1, the lower density clouds also have lower temperature and higher abundance while the higher density clouds have higher temperature and lower abundance. This is counter-intuitive since we would expect denser clouds to be cooler and vice versa. However, such solutions exist too. It is interesting that, as in the case for NGC 3044, the best-fit model gives $T_k(A) = 35 \text{ K}$, because this is very close to the dust temperature obtained from the far-infrared fluxes (34.1 K, see §4.5). Since the free parameters are not well constrained, we also list the *simplest* solution with $T_k(A)$ fixed at 35 K. In this case, solutions in which the temperatures and abundances of the two components are identical are the simplest. Of these, we list the one having the smallest χ^2 fit in Table 4.9 as Model 2. For Model 2, the two types of clouds are

very similar. Their H_2 densities differ by only an order of magnitude.

Our main conclusion from this modeling is that the clouds in the nuclear region are inhomogeneous since the one-component model fails to reproduce the observations (this conclusion is also reached for the clouds in NGC 3044). In addition, at least one type of clouds is of low density ($\geq 1.0 \times 10^4 \text{ cm}^{-3}$). Other authors have also found that one-component modeling is inadequate in describing the clouds in the inner regions of infrared-bright (hence starbursting) spiral galaxies, for example, a sample of 6 spirals (Wall *et al.* 1993) and NGC 1275 (Bridges and Irwin 1997), amongst others. This conclusion in itself is significant and indicates that the physical conditions in the central regions of these galaxies must be complex and that the cloud parameters can not be constrained unless more transitions are observed.

4.4 The Radio Continuum Emission in NGC 5775

We obtained, from Duric *et al.* (1997), the combined VLA B, C and D-configuration maps at 20-cm. The high sensitivity (rms map noise = $55 \mu\text{Jy}$) as well as the high resolution (synthesized beam = $5''$) maps from this data set are presented in Figure 4.17 and 4.18, respectively, and we utilize these maps to compare with results of other wavebands in §4.7.

Figure 4.17 reveals an extensive radio continuum halo reaching as far as 15 kpc above and below the plane of NGC 5775 as well as radio continuum emission between NGC 5775 and NGC 5774. In addition, there is evidence of high-latitude discrete features near $\alpha = 14^{\text{h}}51^{\text{m}}31'', \delta = 3^{\circ}46'24''$ and $\alpha = 14^{\text{h}}51^{\text{m}}20'', \delta = 3^{\circ}44'40''$. Figure 4.18 shows that at high resolution, the radio continuum distribution is far from smooth. There appear to be many discrete features perpendicular to the plane of the

Table 4.9: Sample Two-Component LVG Solutions for NGC 5775

Parameter	Model 1 ^a		Model 2 ^b	
	Type A	Type B	Type A	Type B
$^{12}\text{CO}/^{13}\text{CO}$	25		25	
R_{21} (Theoretical)	0.67		0.70	
R_{32} (Theoretical)	0.54		0.54	
$^{13}R_{21}$ (Theoretical)	0.085		0.088	
$^{13}R_{32}$ (Theoretical)	0.094		0.071	
χ^2 fit	0.20		0.89	
$f f$	3.2×10^{-2}		0.1	
T_k (K)	35	155	35	
n (cm^{-3})	1.0×10^2	3.2×10^3	3.2×10^2	3.2×10^3
$X_{\text{CO}}/(dv/dr)$ pc/(km s^{-1})	1.0×10^{-4}	1.0×10^{-5}	3.2×10^{-6}	
$T_R(^{12}\text{CO} J = 1 \rightarrow 0)$	5.6	37	2.4	17
$T_{\text{ex}}(^{12}\text{CO} J = 1 \rightarrow 0)$	9.0	370	7.2	31
$\tau(^{12}\text{CO} J = 1 \rightarrow 0)$	6.6	0.11	0.92	0.94
$T_R(^{12}\text{CO} J = 2 \rightarrow 1)$	2.8	57	1.1	17
$T_{\text{ex}}(^{12}\text{CO} J = 2 \rightarrow 1)$	7.2	72	5.4	23
$\tau(^{12}\text{CO} J = 2 \rightarrow 1)$	12.2	2.0	1.4	0.36
$T_R(^{12}\text{CO} J = 3 \rightarrow 2)$	0.86	53	0.26	13
$T_{\text{ex}}(^{12}\text{CO} J = 3 \rightarrow 2)$	5.6	61	5.9	20
$\tau(^{12}\text{CO} J = 3 \rightarrow 2)$	4.8	4.3	0.29	5.0
$T_R(^{13}\text{CO} J = 2 \rightarrow 1)$	0.16	7.5	0.047	2.0
$T_{\text{ex}}(^{13}\text{CO} J = 2 \rightarrow 1)$	3.8	38	4.6	12
$\tau(^{13}\text{CO} J = 2 \rightarrow 1)$	0.49	0.26	0.055	0.34
$T_R(^{13}\text{CO} J = 3 \rightarrow 2)$	0.027	6.7	0.0096	0.98
$T_{\text{ex}}(^{13}\text{CO} J = 3 \rightarrow 2)$	0.04	22	6.4	10
$\tau(^{13}\text{CO} J = 3 \rightarrow 2)$	5.2	0.62	0.0075	0.26

^aThis model has the lowest χ^2 value of all the solutions found by letting all 7 parameters in the 2-component LVG model vary.

^bThis model has the lowest χ^2 value of all the solutions with identical temperatures and abundance for the two components.

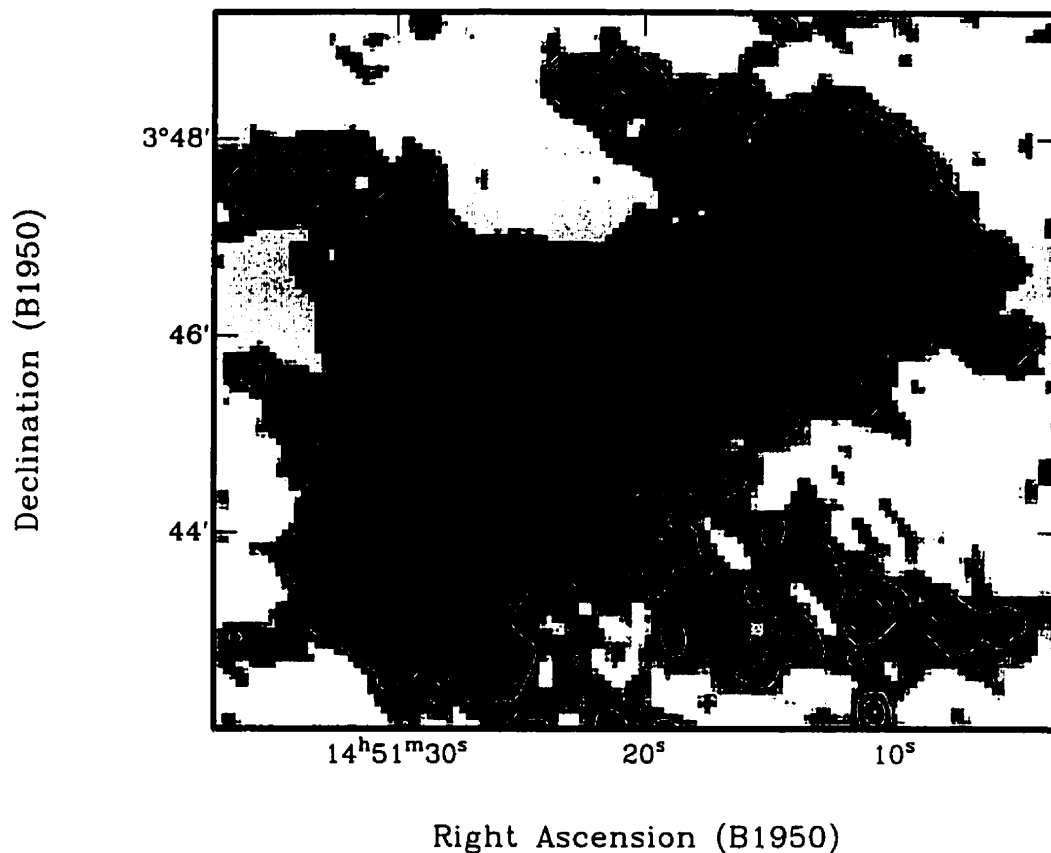


Figure 4.17: 20 cm Combined B, C and D-Array High-Sensitivity Radio Continuum Map of NGC 5775

20 cm radio continuum contours and grey-scale image with synthesized beam of $23''.5$. Contour levels are 0.06 (2σ), 0.12, 0.18, 0.24, 0.30, 0.45, 0.60, 0.90, 1.5, 2.1, 3.0, 9.0, 15 and 30 mJy/beam. Obtained from Duric *et al.* (1997).

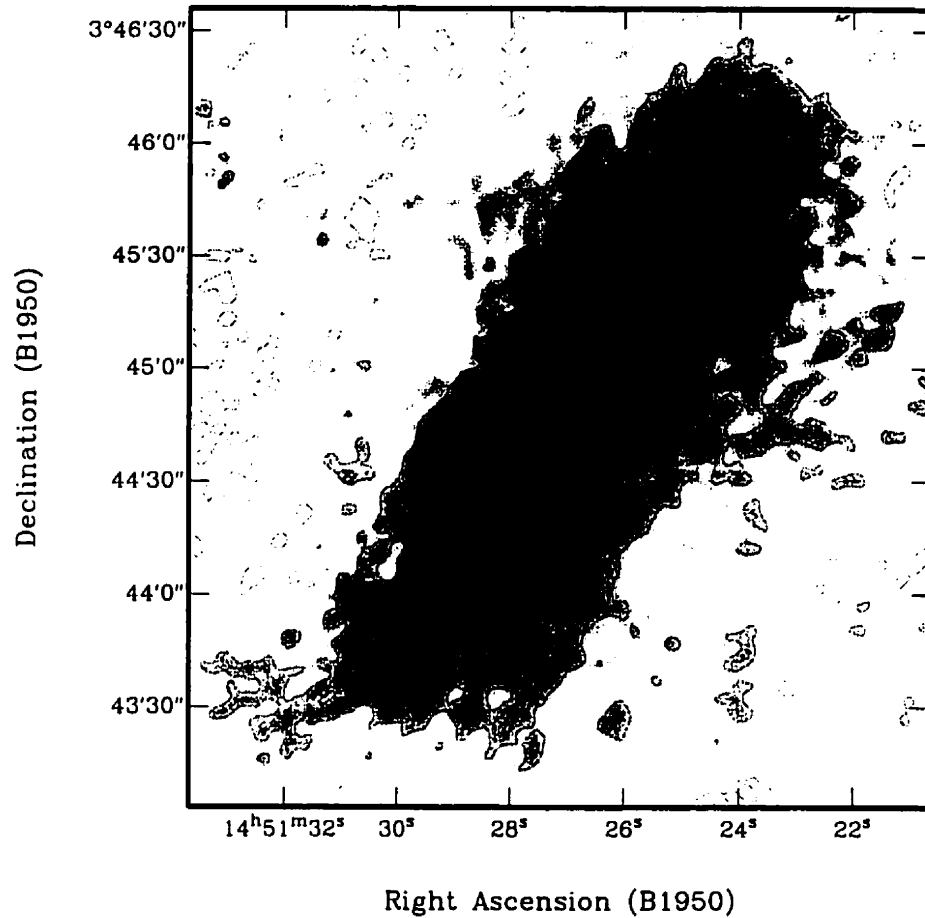


Figure 4.18: 20 cm Combined B, C and D-Array High-Resolution Radio Continuum Map of NGC 5775

20 cm radio continuum contours and grey-scale image with synthesized beam of $5''$. Contour levels are -0.09 , 0.09 (2σ), 0.18 , 0.30 , 0.45 , 0.60 , 0.90 , 1.5 , 2.1 and 3.0 mJy/beam. Obtained from Duric *et al.* (1997).

Table 4.10: Far Infrared Parameters of NGC 5775

$S_{60\mu m}$	23.41 Jy
$S_{100\mu m}$	51.35 Jy
T_d	34.1 K
L_{IR}	$3.8 \times 10^{10} L_{\odot}^a$
M_{dust}	$1.0 \times 10^7 M_{\odot}$
SFR	$2.4 M_{\odot} yr^{-1}$

^a For NGC 5775, the correction factor C in equation 3.22 is 1.44 [from Lonsdale *et al.* (1985)]

galaxy.

4.5 The Far Infrared Emission in NGC 5775

The 60 and 100 μm flux densities of NGC 5775 are obtained from Soifer *et al.* (1989). We did not attempt to colour-correct the flux densities because the correction would change the values by less than 10% (see §3.6). Fluxes from these two wavelengths are used to infer the temperature (equation 3.19), mass (equation 3.21) and luminosity (equation 3.22) of dust in galaxies (see §3.6 for details). Following Condon (1992), a massive star formation rate (SFR) can be estimated using equation 3.24. For NGC 5775, these results are listed in Table 4.10.

We have also obtained high-resolution IRAS (HIRES) images in the four observed bands (12, 25, 60 and 100 μm) of NGC 5775 from IPAC. The resolution enhancement processing (from the low-resolution IRAS data to the HIRES images) was performed at IPAC (see §2.4) and the enhanced beam parameters are given in Table 2.6. The peaks of all four maps are at $\alpha = 14^h 51^m 26.8, \delta = 3^{\circ} 44' 51''$, which is identical to

the coordinates given in the RC3 and also agrees with the radio-continuum peaks. Figure 4.19 displays the contour maps of NGC 5775 for each of the IRAS bands. The most notable feature from these maps is the existence of the far-infrared emission between NGC 5775 and NGC 5774, where the HI bridges are found, indicating that stars are present in the intergalactic region connecting these two galaxies. There are also suggestions of out-of-plane features, e.g., at $\alpha = 14^h51^m23^s.0$, $\delta = 3^\circ44'8''$ in the $12\mu m$ map and $\alpha = 14^h51^m27^s.3$, $\delta = 3^\circ46'44''$ in the $25\mu m$ map.

4.6 The H α Emission in NGC 5775

Figure 4.20 displays the H α image of NGC 5775 (see §2.5 for details). Since the purpose here is to show morphological correlations, the image is not flux calibrated. The H α image reveals an extremely interesting H α disk, with emission reaching as high as 1 kpc at some places (e.g., at $\alpha = 14^h51^m30''$, $\delta = 3^\circ44'35''$, $\alpha = 14^h51^m26^s.4$, $\delta = 3^\circ43'54''$ and $\alpha = 14^h51^m27''$, $\delta = 3^\circ45'55''$). Note that the background level of the image is slightly uneven with the NW side higher than the SE, however, the first contour plotted is two times higher than the high background level, hence we are reasonably confident that the high-latitude emission is real.

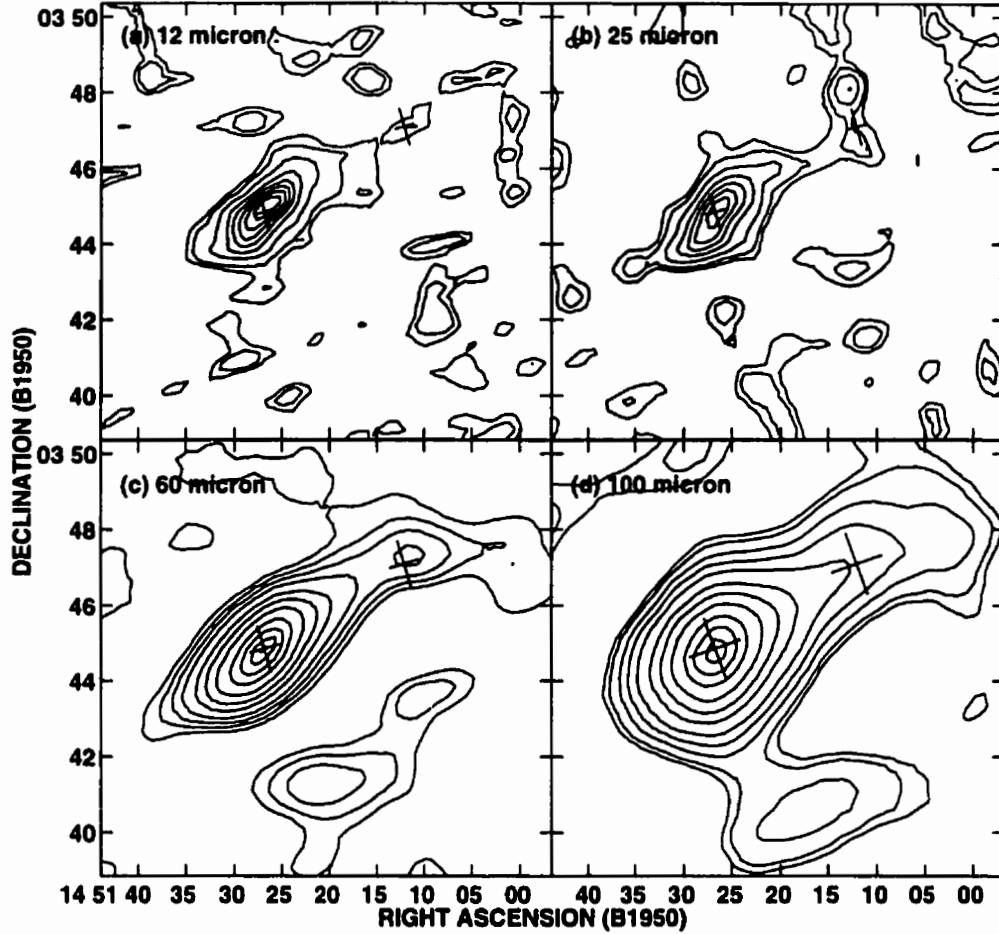


Figure 4.19: HIREs Maps of NGC 5775

(a) $12\mu\text{m}$ map. Contour levels are at 0.33, 0.66 (2σ), 1.65, 3.3, 4.95, 6.6, 8.25, 9.9, 11.55 MJy/ster. (b) $25\mu\text{m}$ map. Contour levels are at 0.47, 0.94 (2σ), 2.35, 4.7, 7.05, 9.4, 11.75, 14.1 MJy/ster. (c) $60\mu\text{m}$ map. Contour levels are at 0.28 (2σ), 0.7, 1.4, 2.8, 7, 14, 28, 56, 84, 112, 126 MJy/ster. (d) $100\mu\text{m}$ map. Contour levels are at 0.23, 0.46 (2σ), 1.15, 2.3, 4.6, 11.5, 23, 46, 92, 138, and 184 MJy/ster. The two crosses in each panel mark the nuclei of NGC 5775 and NGC 5774 and their sizes reflect the restored beam size of that waveband.

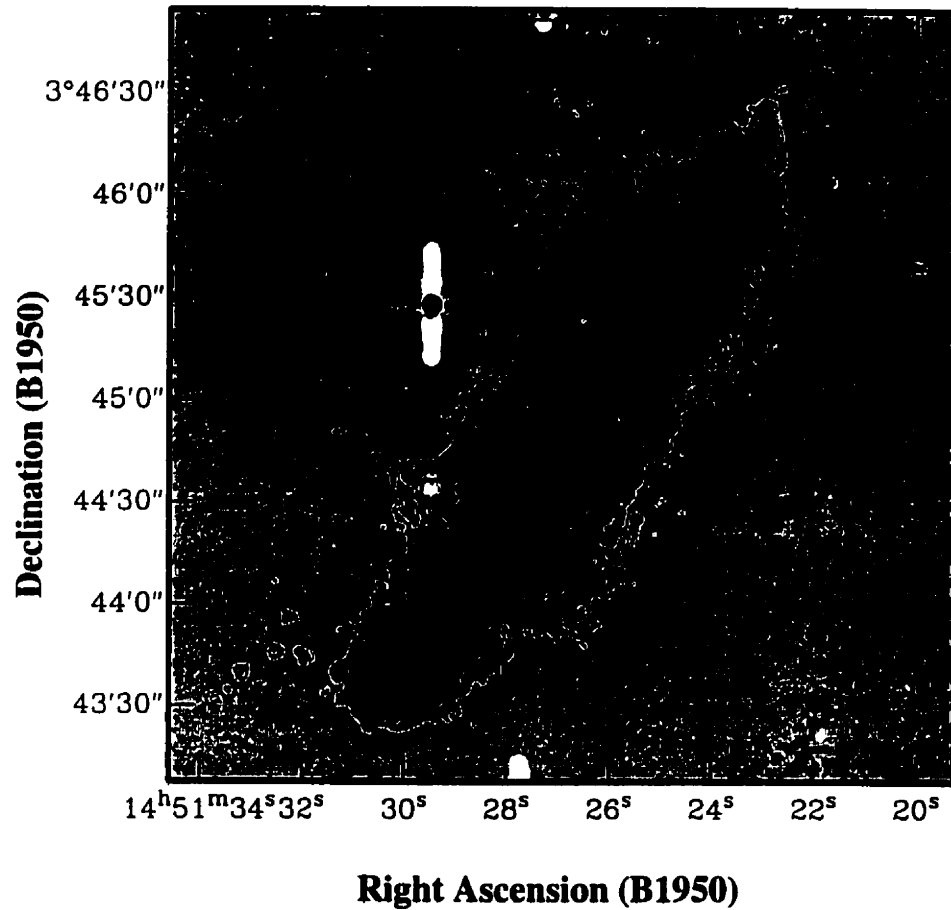


Figure 4.20: The $H\alpha$ Distribution of NGC 5775

The continuum-subtracted $H\alpha$ contours and grey-scale image of NGC 5775. Flux scale is not calibrated and contour levels are at 5, 10, 20, 50, 100 and 150 in arbitrary units. Note the various high-latitude features mentioned in this section and discussed in §4.7.

4.7 Multiband Correlations

In the preceding sections, we have presented results of observations of NGC 5775 in HI, CO, radio continuum, far-infrared and H α . These wavebands trace the distributions of neutral hydrogen, molecular gas, high-energy cosmic rays, warm dust and ionized gas in the galaxy, respectively. It is interesting to compare the galaxy in these different tracers in order to discern their relationships with each other. However, we must bear in mind that the available observations have resolutions that range from a few arc seconds (which corresponds to a few hundred parsecs, H α image) to over one arc minute (corresponds to about 7 kpc, HIRES images). Any correlations (or the lack of), therefore, can only be described qualitatively at this time. In the following, we overlay images and contours of the different ISM components and point out some particularly interesting correlations. Implications of these correlations will be presented in Chapter 6.

Figure 4.21 compares the HI column density distribution (both natural and uniform weighting data) and the 20 cm radio continuum contour map of NGC 5775 and NGC 5774. The radio continuum emission extends beyond the HI emission perpendicular to the disk of NGC 5775 and also exists in the southern HI bridge connecting NGC 5775 and NGC 5774. F3 in the HI image (see Figure 4.3) appears to be related to the high-latitude radio continuum emission reaching as far away as $\alpha = 14^h51^m31''$, $\delta = 3^\circ46'24''$ (14 kpc in projection above midplane). This correlation is more obvious in the uniformly weighted HI map because of its higher resolution. Another HI extension at $\alpha = 14^h51^m22''.5$, $\delta = 3^\circ44'8''$ also seems to coincide with some high-latitude radio continuum emission [Figure 4.21(b)]. These high latitude features will be discussed in detail in the next chapter.

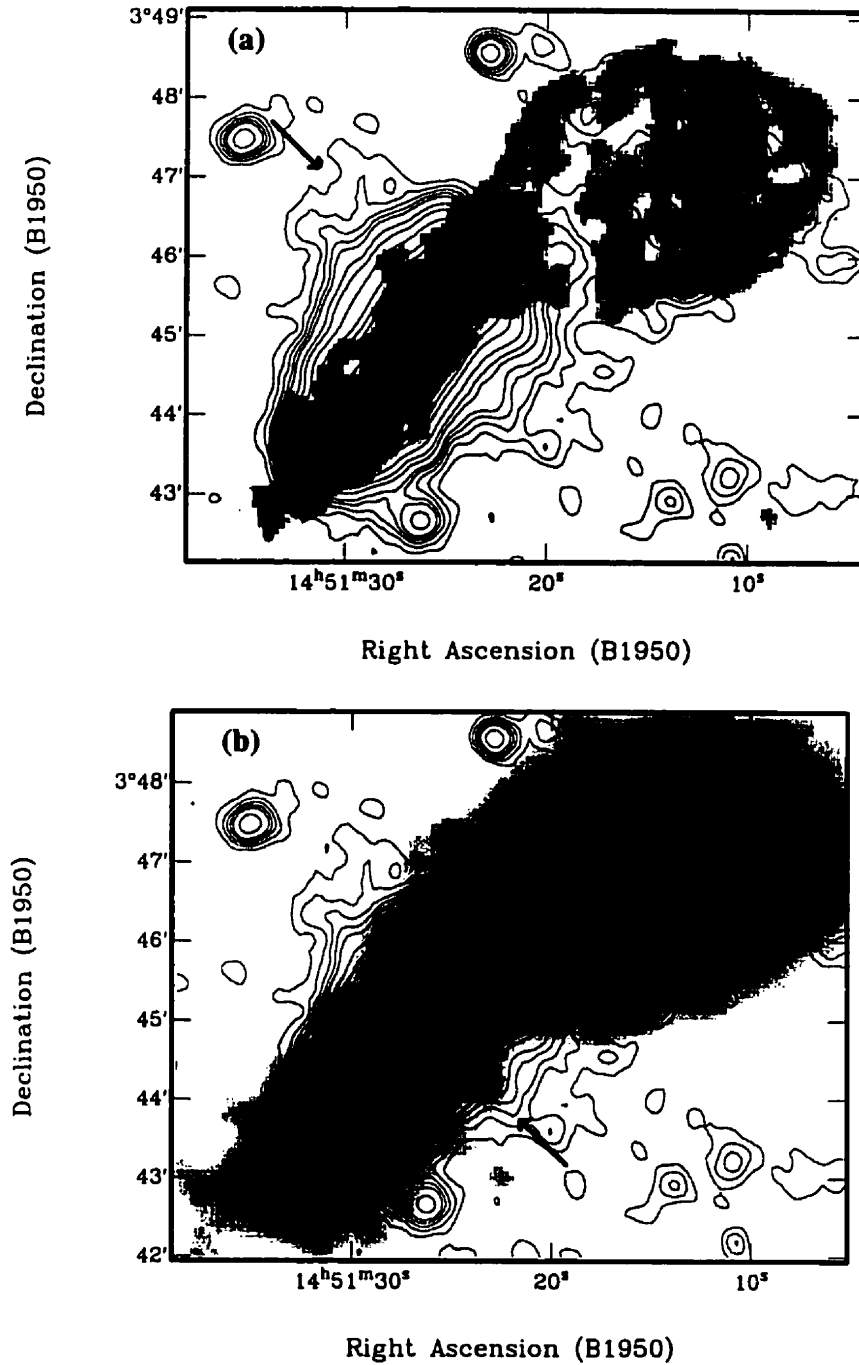


Figure 4.21: HI and Radio Continuum Correlation in NGC 5775

(a) 20-cm combined B, C, and D-array radio continuum contour map (Figure 4.17) is superimposed on the uniformly weighted HI column density grey-scale map. Contours are as in Figure 4.17. (b) as in (a) but the grey-scale image is the naturally weighted HI column density map. Arrows point to the features mentioned in the text.

The far-infrared contour maps are overlaid on the HI column density map separately in Figure 4.22. The 12 and 25 μm maps show far-infrared emission on the southern HI bridge between NGC 5775 and NGC 5774 while the 60 and the 100 μm maps, due to the lower resolution, show only an unresolved connection between the two galaxies. Interestingly, the protrusion at $\alpha = 14^h51^m22'.5, \delta = 3^\circ44'8''$ referred to in the previous paragraph can also be seen in the 12 and the 25 μm maps. The NW extension (at $\alpha = 14^h51^m27'.3, \delta = 3^\circ46'44''$) in the 25 μm map may be associated with F3 which is in the vicinity.

In Figure 4.23, ^{12}CO J=1 $\rightarrow$ 0 and ^{12}CO J=2 $\rightarrow$ 1 integrated intensity contours are superimposed on the HI column density map. In both diagrams, the HI F1 and F2 (see Figure 4.3) sit just above the CO contours which are “pinched”. The ^{12}CO J=2 $\rightarrow$ 1 contours, in particular, seem to suggest a possible CO correlation with parts of 1 and 3 in HI (at $\alpha = 14^h51^m28'.6, \delta = 3^\circ44'52''$ and $\alpha = 14^h51^m27'.5, \delta = 3^\circ45'16''$, respectively). However, due to insufficient sampling, this “correlation” is merely *suggestive* and must await further observations in CO to confirm the high-latitude emission.

Remarkable correlations of high-latitude features can be seen in Figure 4.24, where the H α contours are superimposed on the HI map. F1, F2 and F3 all show H α emission on the *inside edges*. Such correlation has never been observed before and is suggestive of star formation activity *within* the HI features. A more detailed discussion will be presented in Chapter 6. The distribution of H α , CO and radio continuum in the disk are very similar as well (Figure 4.25), especially between the radio continuum and the H α . Both tracers display patterns of patchiness in Figure 4.25(b). Curiously, at $\alpha = 14^h51^m25', \delta = 3^\circ45'40''$, just below the NW high-latitude feature in H α (which is also associated with the HI F3), there appears to be a relatively low intensity region in

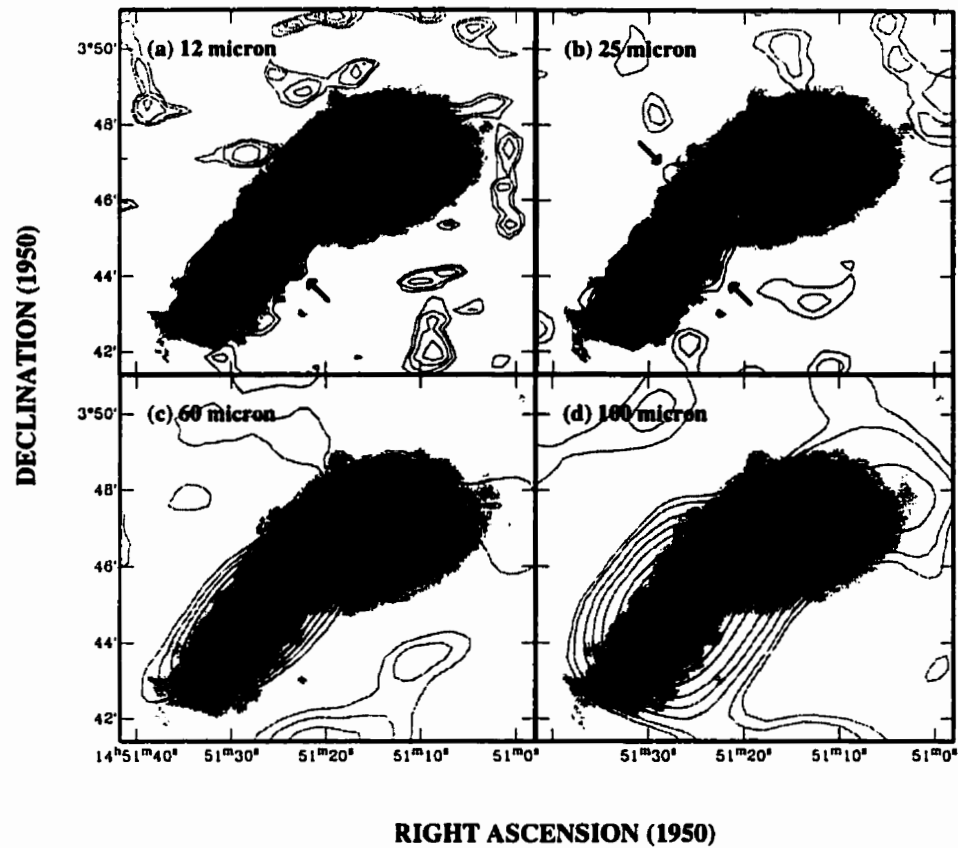


Figure 4.22: HI and Far Infrared Correlation in NGC 5775
 The 4 HIRES images [(a) $12\mu m$, (b) $25\mu m$, (c) $60\mu m$ and (d) $100\mu m$, as in Figure 4.19] are each superimposed on the naturally weighted HI column density map. The contour levels are as in Figure 4.19.

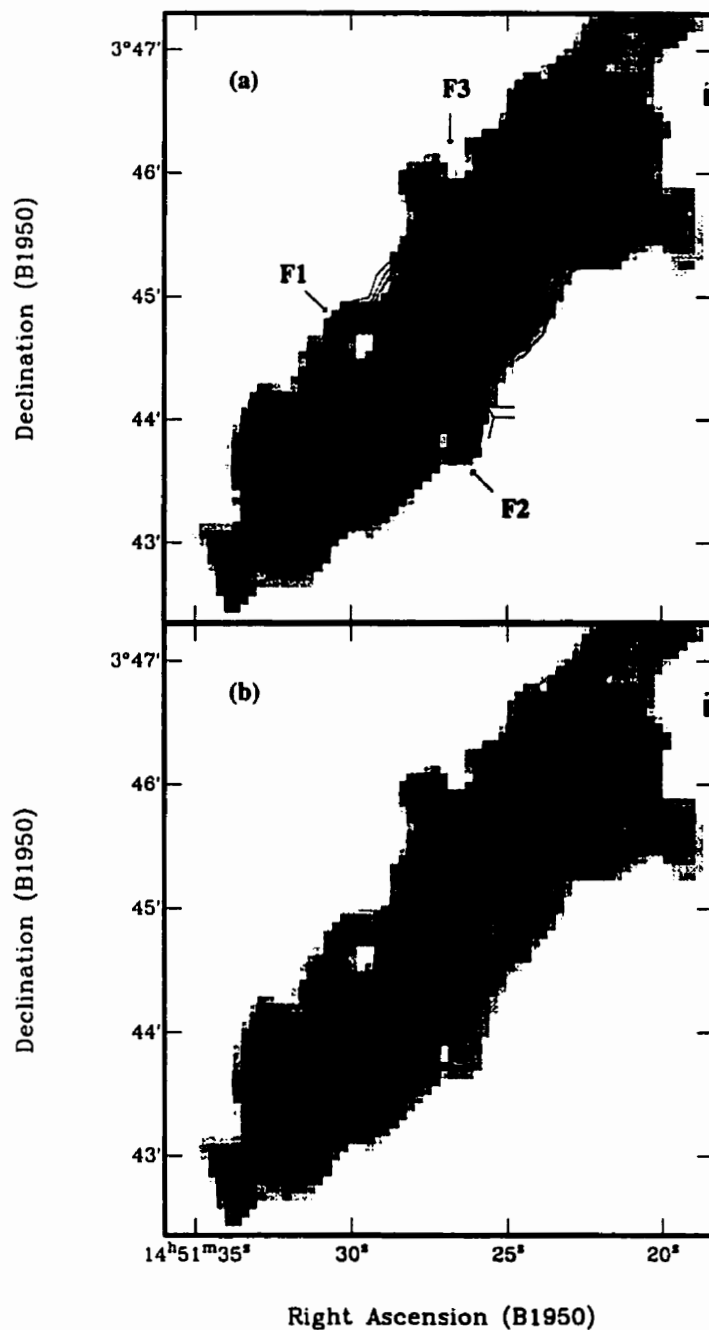


Figure 4.23: HI and CO Correlation in NGC 5775

(a) ^{12}CO $J=1\rightarrow0$ contours of integrated intensity superimposed on the HI column density grey-scale map (only NGC 5775 is displayed). Contour levels are as in Figure 4.13. (b) as in (a), but for the ^{12}CO $J=2\rightarrow1$ contours. Contour levels are as in Figure 4.14.

both the radio continuum and the $H\alpha$ maps. This low intensity region can not simply be due to dust absorption because the radio continuum emission, which is not affected by dust absorption, in this region is similarly low [see Figure 4.25(b)]. The same may be true for the region in the disk below the HI F1 (at $\alpha = 14^h51^m29^s$, $\delta = 3^\circ44'15''$) but there it is not as obvious.

We have seen that the different components of the ISM in NGC 5775 correlate well with each other, with many features being traced in more than one waveband. Most interestingly, the high latitude HI features F1, F2 and F3 all have $H\alpha$ emission located *within* them. These correlations suggest a common origin for the different emission. The best correlation is between the $H\alpha$ image and the high resolution radio continuum map, although part of it is due to the similar beam sizes. The least correlated wavebands seem to be the CO and the dust emission, but the CO coverage is limited and the HIRES images have the poorest resolution of all the data. Better coverage and resolution are needed to draw any firm conclusion regarding their correlation.

4.7.1 The FIR-Radio Continuum Correlation

In Chapter 3, we investigated the correlation between the FIR and the radio continuum as a global parameter of NGC 3044 as well as within the galaxy. We do the same for NGC 5775 here.

The parameter $q = \log[FIR/(3.75 \times 10^{12} Hz)]/S_{20-cm}$ (Helou *et al.* 1985) is a measure of the ratio of the far-infrared to radio fluxes. It has been shown to exhibit very small dispersion (median $\langle q \rangle = 2.3 \pm 0.2$) over a wide range of galaxy types, from quiescence to starburst and from isolated to interacting galaxies (see review by Condon, 1992).

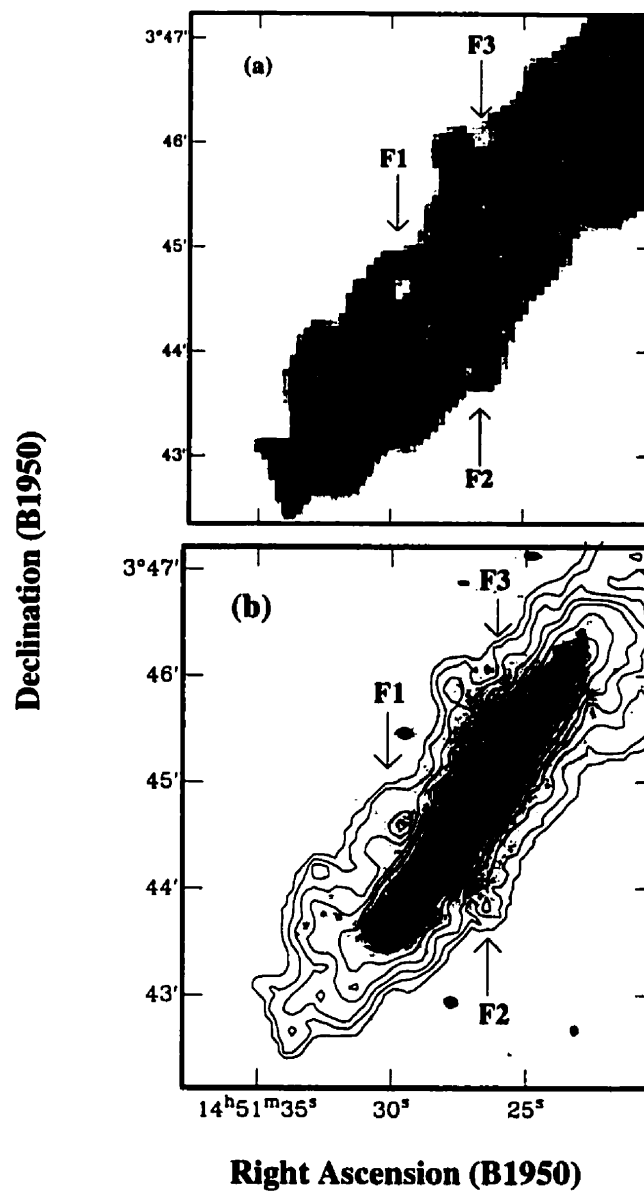


Figure 4.24: HI and H α Correlation in NGC 5775

(a) H α contours superimposed on HI column density grey-scale map to show the correlations in high latitude features. (b) Same as (a) but contours are for HI and grey-scale is H α to compare distributions in the disk.

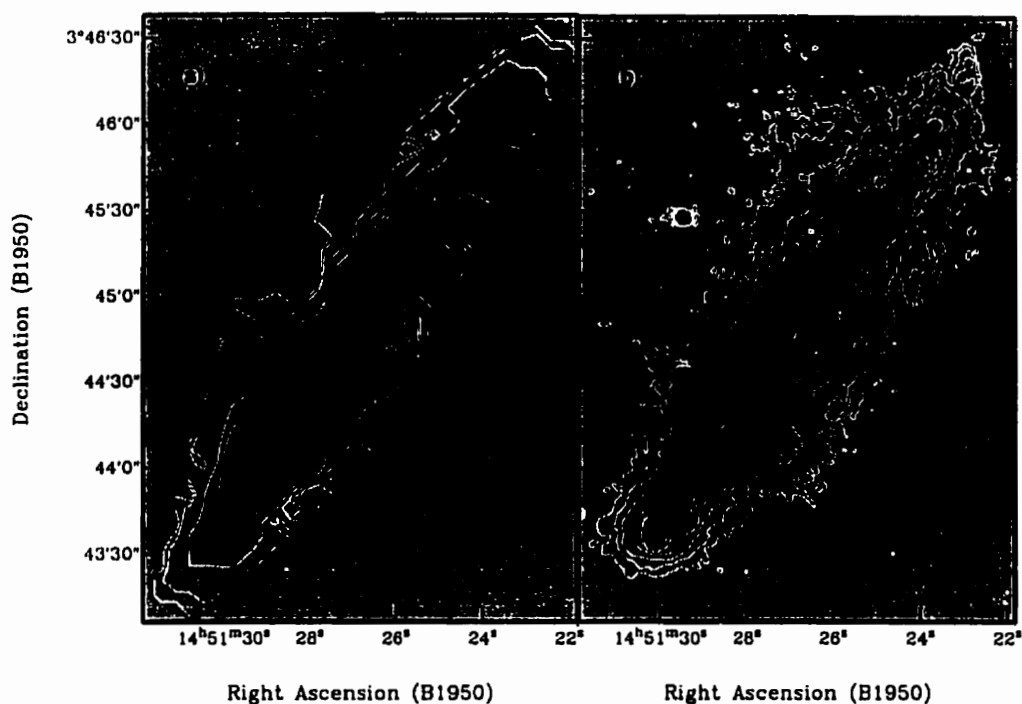


Figure 4.25: High-Resolution Radio Continuum Correlations with H α and CO in NGC 5775

(a) ^{12}CO J=2 $\rightarrow$ 1 integrated intensity contours are superimposed on the high-resolution radio continuum grey-scale map, showing only the disk distribution. Contour levels are as in Figure 4.14. (b) as in (a) but contours are that of H α emission. Contour levels are as in Figure 4.20. Note the “gaps” in both H α and radio continuum in between the two short lines marked on (b) which are mentioned in the text.

The total flux obtained from the 20 cm combined B, C and D-array data ($15'' \times 13''$) is 248 ± 1 mJy (Duric *et al.* 1997). We can compare this value to the value obtained with the Green Bank 91-m single dish telescope (Condon and Broderick 1985). The single dish total flux for NGC 5775 is 221 ± 34 mJy, which agrees with the VLA result. Thus there is no missing flux although the VLA synthesized beam is much smaller. Using the global values of FIR and $S_{20\text{-cm}}$ (Table 4.10), we obtain $q = 2.18 \pm 0.01$ for NGC 5775. This value agrees with the median value stated above. The global correlation shows that a common mechanism is responsible for heating the dust grains as well as accelerating the cosmic-ray electrons. This has been much discussed in literature (e.g., Helou *et al.* 1985, Wunderlich *et al.* 1987, Condon *et al.* 1991). The most likely candidate is young massive stars whose strong ultraviolet radiation heats the dust surrounding them. When these stars eventually become supernovae after about 10^7 years, the supernovae become the energy source for accelerating the cosmic rays.

Combining the $60\mu m$ and $100\mu m$ HIRES maps with the VLA 20 cm map, we can obtain the distribution of the q parameter within the galaxy. We first smooth both the $60\mu m$ and the radio maps to the resolution of the $100\mu m$ map. The $60\mu m$ and $100\mu m$ maps are then combined according to equation 3.23 to give the map of the far-infrared flux. Finally, this far-infrared map is divided by the 20-cm radio continuum map to form the q parameter map (Figure 4.26). A 1σ cutoff was applied to both the far-infrared and the radio continuum maps before dividing.

For NGC 5775 itself, q peaks near the galaxy's centre at a value of 2.30. The ratio decreases with increasing radius from the nucleus out to about $75''$ radius. The average q in NGC 5775 is found to be 2.03 ± 0.20 (s.d.) while the uncertainty of the q parameter map due to the noise in the input maps is only about 0.01 in the log. This

decreasing trend is consistent with that seen in other galaxies (e.g., Bica and Helou 1990, Fitt *et al.* 1992) as well as in NGC 3044 presented in Chapter 3. Beyond that, the q values rise again on the NW and SE sides of the galaxy. On the NW side this parameter reaches a maximum again between the two galaxies. On the SE, q rises because the position angles of the FIR map and the radio map are slightly different, with the FIR map having a smaller position angle than the radio contours. This is probably due to the fact that the 60 and the $100\mu m$ data cannot resolve the bridges connecting the two galaxies, causing the unresolved intensity contours to tilt towards NGC 5774. The rise in q on the NW is much more difficult to explain. The dust and energetic particles may both have been dragged out from one of the interacting galaxies (probably NGC 5774, see Irwin 1994), or they may have been produced *in situ*. Unfortunately, $H\alpha$ emission in the bridges was not detected due to the high background level in the $H\alpha$ image. It would be interesting to see what is the level of star formation activity in this region.

As discussed in Chapter 3, a centrally peaked q distribution in galaxies has previously been interpreted as being due to cosmic ray diffusion causing the radio scale length to be greater than the FIR scale length in the plane of the galaxy (Bica *et al.* 1989, Bica and Helou 1990). On the other hand, the $H\alpha$ distribution of NGC 5775 correlates well with the radio continuum distribution in the disk (see Figure 4.25), with many discrete clumps all along the disk. If we assume the $H\alpha$ distribution also traces the warm dust distribution, then in order to explain the declining q , the contribution of the ambient radiation field out in the disk must dominate over the UV radiation from the HII regions traced by the $H\alpha$ emission. The relative contribution of the far-infrared emission by warm and cold dust requires higher resolution far-infrared data as well as detailed modeling which is not possible here.

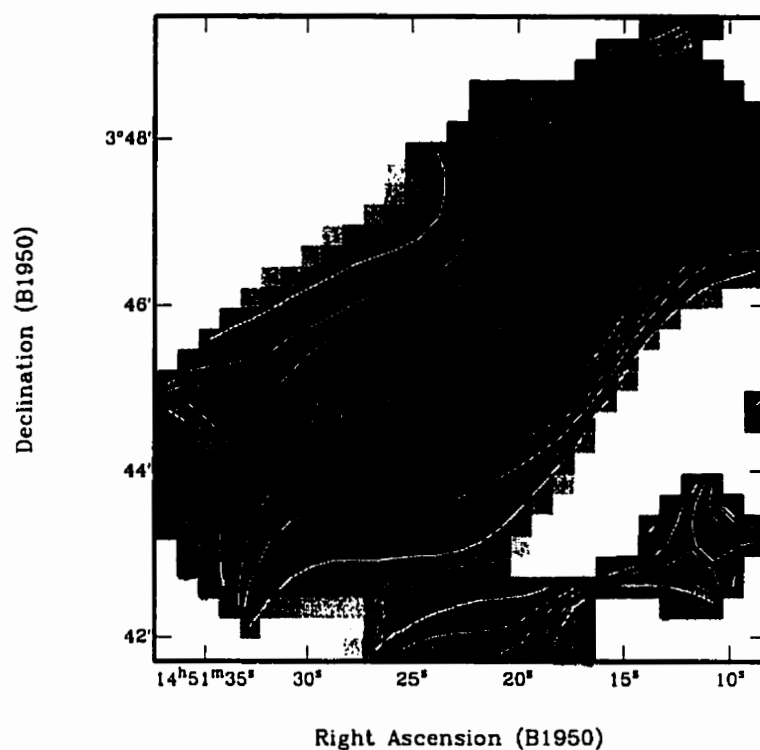


Figure 4.26: FIR-to-Radio Continuum Ratio in NGC 5775

Contours and grey-scale representation of the FIR to radio continuum ratio of NGC 5775 in Log. Contours are at 1.8, 2.0, 2.1, 2.2, 2.25, 2.28, 2.3, 2.4, 2.5, and 2.6. The crosses are located at the RC3 position of NGC 5775 and NGC 5774 and reflect the size and orientation of the $100\mu m$ beam.

4.8 Summary

The edge-on, infrared-bright galaxy NGC 5775 has been mapped in HI. The global profile parameters indicate a normal galaxy of the SBc morphological type, despite its interaction with NGC 5774. Various high-latitude features are observed, with the most extended one reaching roughly 7 kpc above the plane of the galaxy. The HI distribution has a central depression with two peaks on the NW major axis and one peak on the SE side. The outer, and stronger NW peak is possibly enhanced by the inflow of gas from NGC 5774. Modeling of the data cube indicates that the HI is distributed in a ring with the maximum volume density located at the outer NW peak. The vertical distribution has a large scale height of 1.1 kpc, larger than the corresponding value for the Milky Way Galaxy and consistent with the thick radio continuum disk reported by Hummel *et al.* (1991) and Duric *et al.* (1997).

^{12}CO J=1 $\rightarrow$ 0 and ^{12}CO J=2 $\rightarrow$ 1 line emission was mapped along the major axis and in the inner part of the galaxy close to the nucleus. The inferred molecular distribution is centrally peaked with some indication of possible high-latitude emission. Further high-z observations would have to be carried out to confirm this. Spectra at the nucleus of the galaxy in all transitions show high velocity red- and blue-shifted wings. Either a rapidly rotating disk or a molecular outflow can explain this emission. The R_{21} line ratio was obtained for region within a radius of 7 kpc (60"). There is no spatial variation in this parameter to within observational uncertainties. A two-component LVG model is necessary to reproduce the observed line ratios indicating that clouds in the central region are complex and can not be described by a simple homogeneous model. We find that at least one type of clouds must have low density ($\leq 10^4 \text{ cm}^{-3}$) near the nucleus. More observations are needed to further constrain

other cloud parameters.

Radio continuum and HIRES images both show the southern bridge connecting the two galaxies but the bridge was not detected in the $H\alpha$ possibly due to the high background level.

The various components of the ISM show some striking correlations. The HI high-latitude features F1, F2 and F3 are also seen in the other wavebands. For example, features which may be associated with F3 are found in the radio continuum, in the $25\mu m$ map, in the $H\alpha$ image and is hinted at in the CO map. In particular, the correlations of these features between the $H\alpha$ and the HI maps are especially tantalizing, with the $H\alpha$ features lying *within* the HI features. The high-resolution radio continuum and the $H\alpha$ distribution in the disk both show breaks in activity in the disk just below F1 and F3.

The high-latitude features will now be discussed in detail in the next chapter.

Chapter 5

The HI Supershells in NGC 3044 and NGC 5775

As alluded to in Chapters 3 and 4, NGC 3044 and NGC 5775 show a host of high latitude features, some of which resemble either broken or complete loops or shells. Some of these features are amongst the largest found to date. No doubt this is due to selection effects since these two galaxies are also the more distant ones amongst those galaxies in which HI supershells are found. In this chapter, we present detailed analysis of the HI high-latitude features in these two galaxies. We estimate their sizes and examine whether there are signatures of expansion and if so we refer to them as expanding supershells. Due to the edge-on orientation of these two galaxies, only features energetic enough to reach high latitude can be identified. Also, the velocity resolutions of the HI data (20 km s^{-1} for NGC 3044 and 40 km s^{-1} for NGC 5775) prevent us from identifying features which have velocity ranges smaller than 10 km s^{-1} for NGC 3044 and 20 km s^{-1} for NGC 5775. §5.1 gives a brief explanation of the velocity signature of an expanding shell. §5.2 presents the analysis of the features in NGC 3044 and gives lists of shell parameters. §5.3 contains a parallel discussion as in §5.2 but for the features in NGC 5775. If the expanding supershells are produced by supernovae, the required energies can be calculated. We present these calculations in §5.4. The origin and implication of these supershells are deferred to the next chapter.

5.1 Evidence of Supershells

There is no question that high latitude HI features exist in both NGC 3044 and NGC 5775. We identify these features by visually inspecting the velocity channel maps for features that appear at the same spatial location in at least two consecutive velocity channels. In addition, we summed neighbouring velocity channels in systematically increasing number of channels (i.e., formed moment-zero maps). Any coherent high latitude feature would stand out more prominently when the appropriate channels were added. In order to find out if these features are expanding or stationary, we have to examine their velocities. In passing, we mention here that the diagnosis discussed here can not distinguish between an expanding shell and a contracting one. Following common practice, if a feature is found to have velocity signature of a moving shell, we will refer to it as an expanding shell.

The most direct, and commonly used, method is to examine the p-v diagram of a slice (much like the major axis p-v diagrams shown in the previous two chapters) that cuts across the feature in question. If the features are actually expanding shells or partial shells, they should appear as rings or partial rings in the p-v slices (see Figure 5.1). Imagine a spherically symmetric thin shell of gas expanding into its surrounding medium at some velocity V_{sh} with respect to the velocity at the centre of the shell. The velocity of the approaching hemisphere of the shell will appear blue-shifted wrt to the centre velocity and the receding side red-shifted. From our view point, the two limbs of the shell (in the directions of B and B' in Figure 5.1) will appear brighter (higher intensity) because we are looking through more gas along the shell walls. Towards the centre of the shell (along the line AA') the intensity will drop. As we scan across the shell from limb to limb, the l-o-s velocity will change from zero

(owing to the part of the shell that is moving tangentially to us) to a maximum of $\pm V_{sh}$ towards the centre of the shell due to the approaching (point A') and receding (point A) caps and back to zero towards the other limb.

Equivalently, one can identify an expanding shell by examining the individual velocity channel map, if the spatial and velocity resolution is smaller than the shell radius and expansion velocity, respectively. The shell should appear to change in radius with velocity. At the highest relative velocity (V_{sh}), the shell will have the smaller angular extent because we are looking at the approaching or receding cap. At some projected radius away from the shell centre, the shell gas will have the same foreshortened l-o-s velocity, we will therefore see a larger ring or disk at this velocity channel. The largest angular size will be seen in the velocity channel which corresponds to shell gas moving in a nearly tangential direction from us.

In reality, the situation is of course much more complicated. The expanding shell will be embedded within the HI disk. So we have to distinguish the shell from the disk gas. If the expansion velocity of the shell is not particularly high, it may not be detected as it will be confused with normal disk gas. This does not, however, pose serious problem with shells that have reached high latitude, and we have chosen edge-on galaxies to study for this very reason. If the expanding shell is located near the edge of the disk, then one hemisphere will be expanding into denser medium. This hemisphere may decelerate very rapidly causing the shell to look like a partial ring in the p-v slice. Furthermore, if the surrounding ISM is not homogeneous, the shell may not be spherically symmetric and the expansion velocity may vary with position. All these effects, coupled with the fact that we are limited by the spatial and velocity resolutions of the observation contribute to make identifying an expanding shell a difficult and partially subjective task.

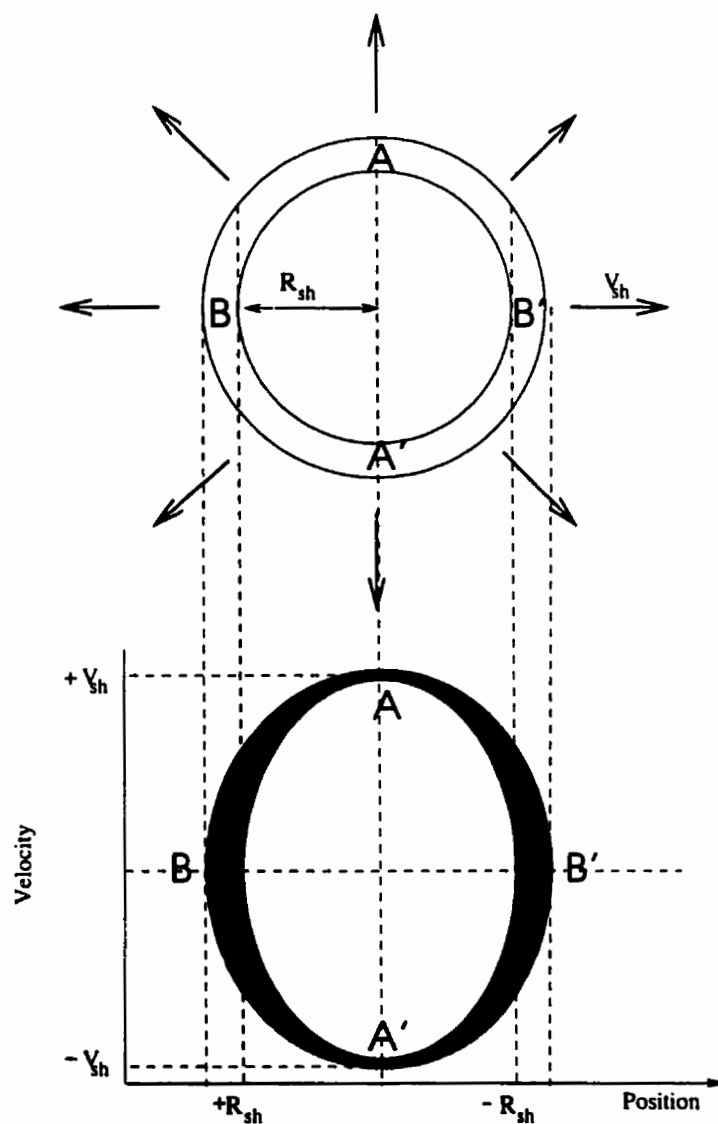


Figure 5.1: Schematic Diagram of An Expanding Shell in Position-Velocity Space
 This diagram depicts what a slice of a spherically symmetric expanding shell would look like when plotted in the position-velocity space. See text for explanation. The reader should think of the thickness of the black border as the intensity of the gas, with the intensity smallest towards the position of the centre of the shell and largest towards $\pm R_{sh}$.

If a feature is stationary, then obviously it will not be detected in the p-v slice as described above. However, it will still be present in the velocity channel maps, but will not change in spatial extent in the different channels. In addition, the velocity range for a stationary feature should be narrow because otherwise it will indicate that the velocity dispersion in the feature is large. A large velocity dispersion that is not caused by expansion can only be attributed to turbulent motion. It will be difficult for a self-contained unit with high velocity dispersion to survive breaking up and reach a height of a few kpc. Finally, if a feature is instead a spur ejected from the disk or a 2-dimensional loop, then we should see a small range of velocity either all red-shifted or all blue-shifted wrt to the expected radial velocity, but not both.

5.2 High Latitude Features in NGC 3044

In this subsection, we present the analysis of the high latitude features in NGC 3044. The work shown here is published in Lee and Irwin (1997).

The naturally weighted channel maps in Figure 3.2 and 3.3 display numerous low intensity, high-latitude arcs and extensions away from the disk of NGC 3044. They appear to be distributed randomly along the disk of the galaxy. These arcs and extensions in NGC 3044 resemble the so-called “Heiles Shells” in our Galaxy. The integrated intensity map in Figure 3.22 reveals the more distinct features (F3, F6 and F10). The other features do not show here because of confusion with gas from other velocity channels. In order to identify features that show up in more than one consecutive channel, we examine the individual velocity channel shown in Figure 3.2 in some detail and, in conjunction, integrate various number of successive channels to find the best range of velocity for each feature and their position. In this manner,

we catalogued 12 high latitude features (Feature 1, or F1, to Feature 12 or F12). Table 5.1 lists their positions, velocity ranges and the highest projected z-extents (measured from midplane in the direction perpendicular to the plane) at the 1.5σ level. The velocity ranges are from the centre of the first channel to the centre of the last channel in which the feature is identified. Some of these features have very complex appearances and are probably the results of blended features along the same line-of-sight (e.g., F3). Table 5.1 is by no means exhaustive. The selection of the features are subjective and are limited by our ability to recognize only the obvious ones. Finally, it is possible that some of the features in Table 5.1 may in fact be related in a complex way (e.g., F9, F10 and F11 are located closed to each other spatially and in velocity; F7 refers to the hole in HI and it is possible that F3 is part of F7's eastern rim). Figures 5.2 and 5.3 display the same channel maps as in Figure 3.2 but are enlarged and included arrows to show the features we identified.

In the following we describe a few interesting features with the aid of the integrated intensity maps. These maps are obtained by integrating over those channels listed in Table 5.1 appropriate for the feature of interest. F4 and F7 are shown in Figure 5.4 and 5.5, respectively. Their integrated intensity maps show that they are circular or nearly circular holes where the HI gas interior to them appear to have been depleted. In the velocity channel maps (Figure 3.2), F4 is most obvious at 1339 km s^{-1} and F7 is most obvious at 1297 km s^{-1} . F6 is shown in Figure 5.6. This feature can be seen in velocity that straddles the systemic velocity (1287 km s^{-1}), hence we may be seeing both the receding and the approaching caps of an expanding shell on the northeast side of the galaxy (see below). In the integrated intensity map, it resembles an open-topped loop. Feature 10 (Figure 5.7) is the most massive (see Table 5.3) extension in the list and spans 7 velocity channels. At 1172 and 1152 km s^{-1} , F10

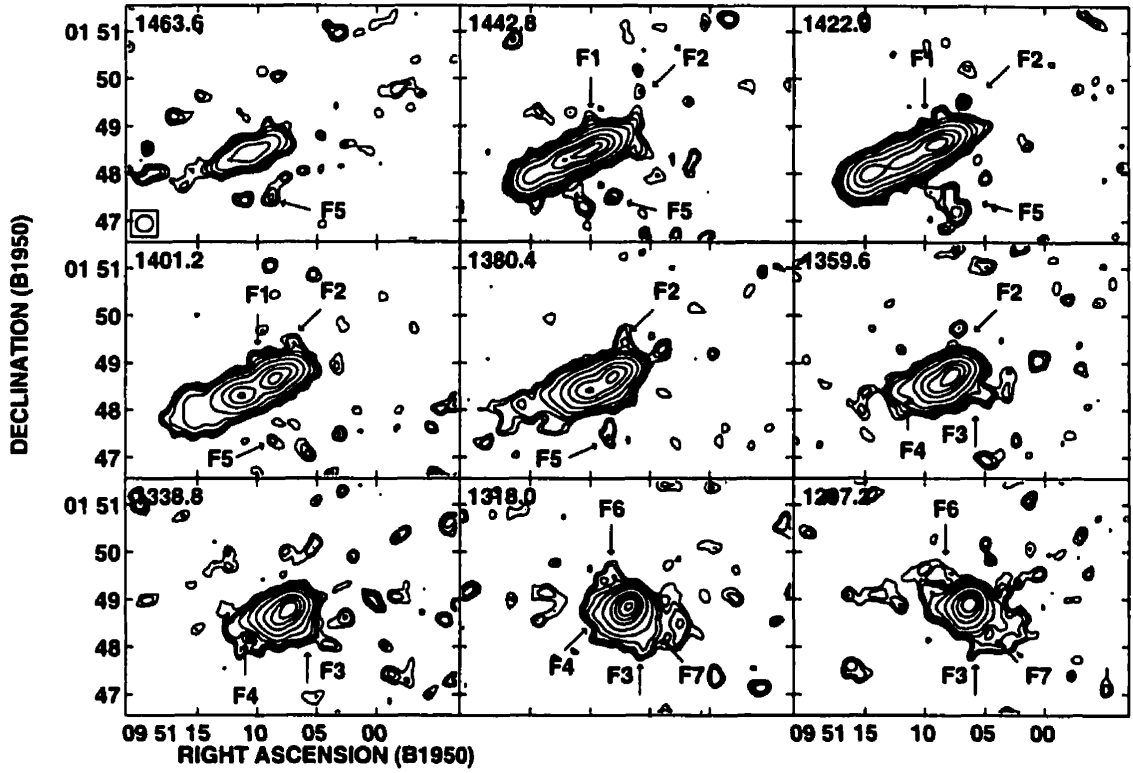


Figure 5.2: Channel Maps Showing High Latitude Features in NGC 3044
The natural weighting channel map with contour levels at 0.76 (1.3σ), 1.0, 1.3, 1.9, 3.2, 6.4, 12.8, 19.2, 25.6, 32.0, 38.4 and 44.8 mJy/beam. Arrows are included to show the identified features.

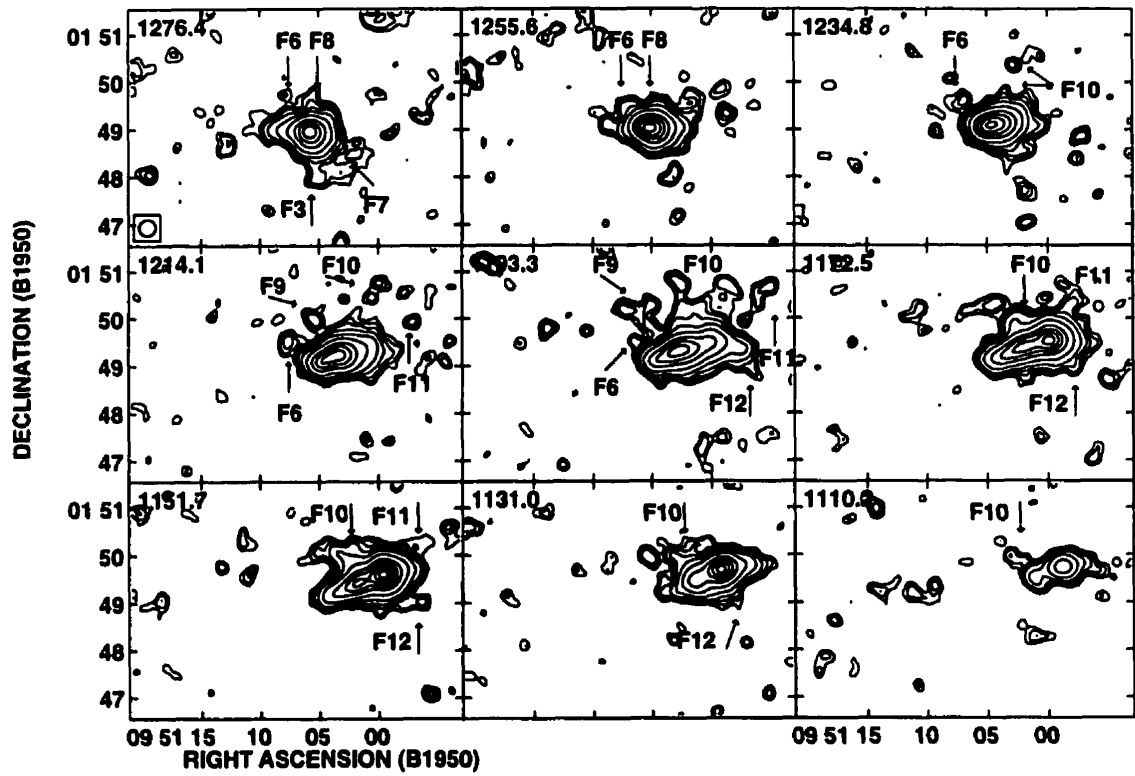


Figure 5.3: More Channel Maps Showing High Latitude Features in NGC 3044
A continuation of Figure 5.2.

Table 5.1: High-Latitude Features in NGC 3044

Feature	R. A. <i>h m s</i>	Dec. <i>° ' "</i>	Velocities km s^{-1}	No. of Channels	z-Height kpc
F1	9 51 9.8	1 49 5.0	1401.2 to 1442.8	3	3.9
F2	9 51 6.9	1 49 21.0	1359.6 to 1442.8	5	4.7
F3	9 51 5.0	1 48 17.0	1276.4 to 1359.6	5	8.0
F4	9 51 10.6	1 48 13.0	1359.6 to 1318.0	3	-
F5	9 51 7.7	1 47 21.0	1380.4 to 1463.6	5	11.2
F6	9 51 9.5	1 49 5.0	1193.3 to 1318.0	7	6.7
F7	9 51 4.7	1 48 17.0	1276.4 to 1318.0	3	-
F8	9 51 6.9	1 49 29.0	1255.6 to 1276.4	2	4.9
F9	9 51 5.3	1 50 1.0	1193.3 to 1214.1	2	8.8
F10	9 51 2.6	1 50 0.0	1110.2 to 1234.8	7	9.5
F11	9 50 58.9	1 50 2.0	1151.7 to 1214.1	4	6.5
F12	9 50 57.8	1 49 0.0	1131.0 to 1193.3	4	6.9

bends towards the east at high latitude so that it looks like an arc. A large region near F10 is disturbed, hence F10 may actually be a blend of many features. The position indicated for F10 in Figure 5.7 is the position obtained from the p-v slice (see below). F12 can also be seen in Figure 5.7. Another interesting feature, F5 (see Figure 3.2) reaches 11.2 kpc above the midplane (most obvious at 1422 km s^{-1} where it could be disconnected from the disk), making it the most extended feature of all.

Figure 5.8 and 5.9 show the integrated intensity maps of features 4, 7, 10 and 12 and their associated p-v diagrams (natural weighting data). These features are chosen to be presented here because they display velocity signatures of expanding shells. The other features either do not show such signature (perhaps because they are stationary or are not shells) or any velocity features present are uncertain (e.g., F6, see below) and will not be discussed here. However, it should be kept in mind

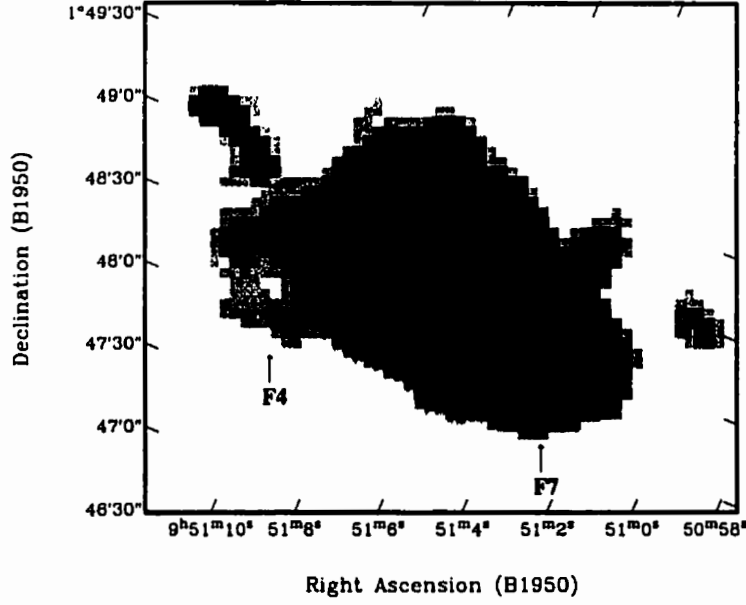


Figure 5.4: Integrated Intensity Map of Feature 4 in NGC 3044
The intensity is integrated over the velocity of 1318.0 km s^{-1} to 1359.6 km s^{-1} . The galaxy has been rotated so that the major axis is horizontal.

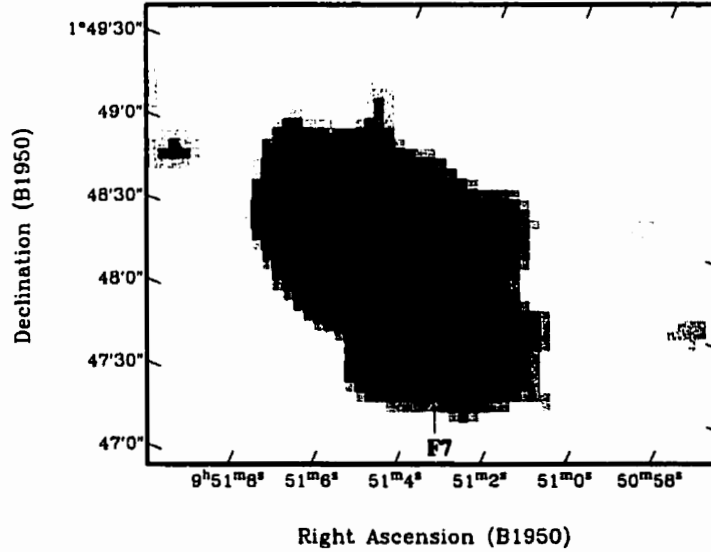


Figure 5.5: Integrated Intensity Map of Feature 7 in NGC 3044
The intensity is integrated over the velocity of 1276.4 km s^{-1} to 1318.0 km s^{-1} .

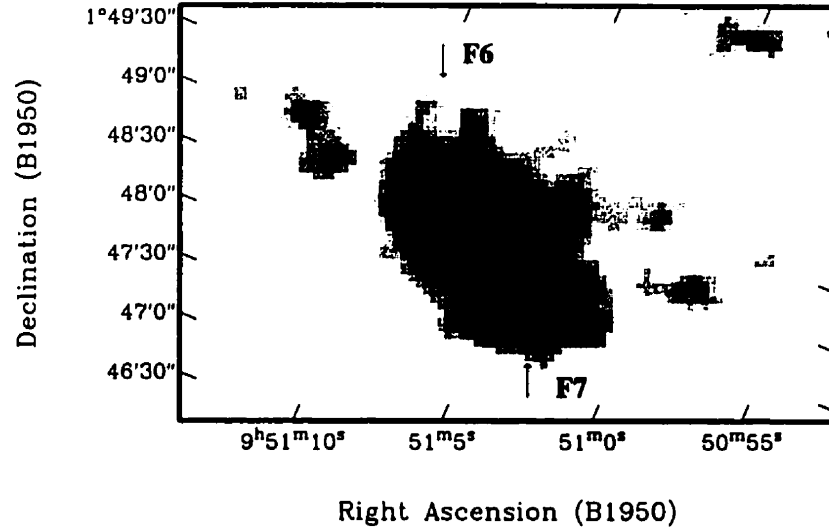


Figure 5.6: Integrated Intensity Map of Features 6 and 7 in NGC 3044
The intensity is integrated over the velocity of 1193.3 km s^{-1} to 1318.0 km s^{-1} .

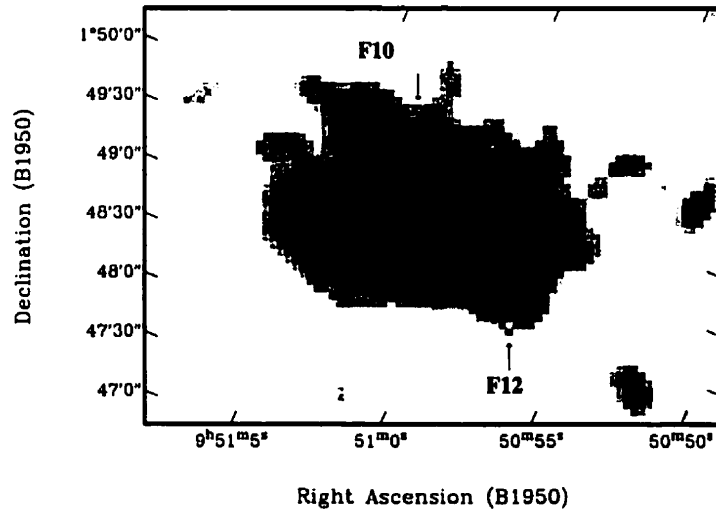


Figure 5.7: Integrated Intensity Map of Features 10 and 12 in NGC 3044
The intensity is integrated over the velocity of 1110.2 km s^{-1} to 1234.8 km s^{-1} .

that whether they are expanding or not, their existence at high latitude suggest that some energetic events in the past must have occurred to force the gas out of the plane of the galaxy. Also, they represent gas that is fed into the galaxy's halo, hence constitute one component of the disk-halo interaction in this galaxy.

The integrated intensity maps are similar to those shown in Figure 5.4 to 5.7. But for features having similar velocity ranges (e.g., F4 and F7, F10 and F12), we simply show a common integrated intensity for both. The p-v diagrams are those of the slices shown in the column density maps (but note that the p-v slices are calculated from the data cube, not the column density maps). Each slice is an average of 2 pixels (8") parallel to the major axis. In each p-v slice shown, we find expansion signatures at the position and velocity corresponding to these features. The three panels in each of Figures 5.8 and 5.9 have the same scale in the major axis offsets and are aligned so that the positions of the features can be obtained by dropping a vertical line across the page from the top panel. We shall name the p-v diagrams in Figure 5.8(ii) and (iii) and Figure 5.9(ii) and (iii) as slice 1 through 4, respectively, for ease of reference. Slices 1, 2 and 4 present the p-v diagrams cut along lines 24" (2.4 kpc), 40" (4 kpc) and 48" (4.8 kpc) below the midplane (parallel to the major axis) and slice 3 is a cut of 40" above the midplane. Note that for any one particular feature shown in Figures 5.8 and 5.9, similar signatures are seen in other slices cut at different z-height from the plane (not shown). For example, emission from F7 also appear in slices 1 and 4 but is best seen in slice 2. The p-v slices shown here are picked such that they show the velocity signatures best.

From Figures 5.4 to 5.7, in the directions towards the named features *and* within the velocity ranges given in Table 5.1, we find arc-like contours which we point out using arrows in the p-v diagrams. That is, in all cases, the shells are not complete

but are “open” at the sides toward lower density, both in p-v and in RA-DEC space. This is consistent with the Chimney models for a blow out case (see Chapter 6). It could also indicate that the shell has more readily fragmented in low density regions. In Figure 5.8(ii), the higher intensity gas surrounding the hole, F4, corresponds to gas moving at lower velocity relative to the regularly rotating disk gas. Hence these gases are likely to have the l-o-s velocity component pointing towards the observer. The hemisphere moving away is not seen, which could mean this hole is located near the edge of the disk closest to us. Emission at offset of about $-70''$ and velocity at 1350 km s^{-1} can be seen in Figure 5.8(ii). These gases do not following the normal rotation of the disk. We find that these gases appear to be associated with F7 but the exact relation is unknown. Figure 5.8(iii) shows the best example of an expanding feature in NGC 3044, i.e., F7. This feature is almost completely circular, with the receding cap of the feature missing.

As mentioned before, the spatial structure of F10 is complicated. What appears to be the arc-like feature is actually to the east of the centre of the expanding velocity signature in Figure 5.9(ii). We suggest that F10 is part of a more extended and disturbed complex in this part of the galaxy. We have also indicated the possible expanding shell signature of F6 in Figure 5.9(ii). The loop-like contour is only at the 1σ level, we therefore do not include F6 as one of the expanding features. For F12 [Figure 5.7], although it appears to be simply a vertical extension out of the plane rather than a loop or an arc in the total intensity map, its velocity signature can be traced in more than one neighbouring slices. We therefore include F12 as one of the expanding shell features.

Of the 12 high latitude HI features catalogued in Table 5.1, 4 of them show distinct associated expanding shell signatures. F4 and F7 are holes in HI. They are likely

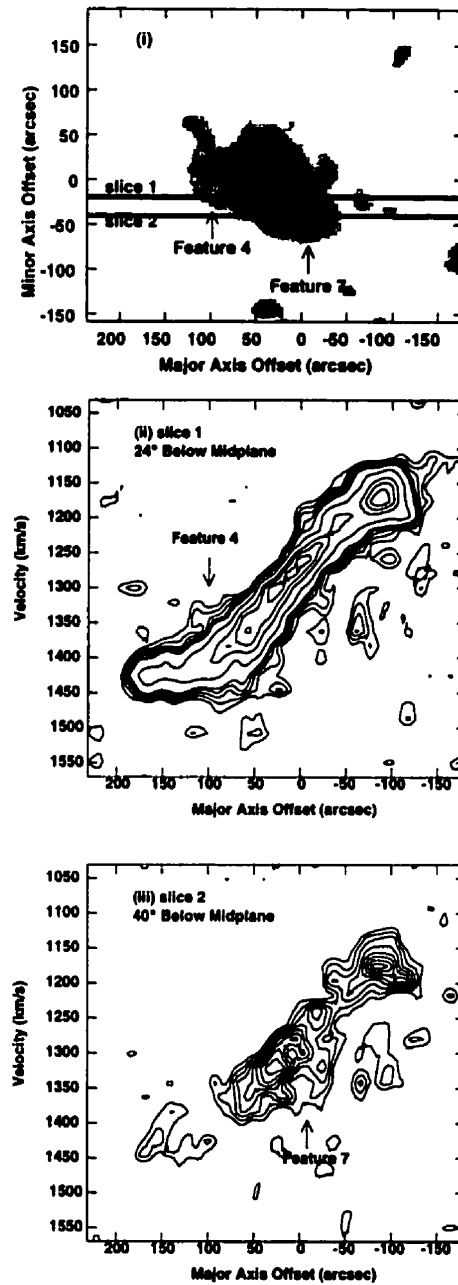


Figure 5.8: Integrated Intensity and P-V Diagrams for Features 4 and 7 in NGC 3044 (i) Integrated Intensity map showing Features 4 and 7. Smoothing is done as in Fig. 3.5. (ii) and (iii) show p-v slices corresponding to cuts along the two horizontal lines in (i), which are parallel to the major axis. Each slice is an average of 2 pixels ($8''$). Contours are at 0.64 (1σ), 1 , 1.3 , 1.6 , 1.9 , 3.2 , 5.1 , 6.4 , 7.7 mJy/beam. The slice number and height below the midplane are shown in each p-v panel.

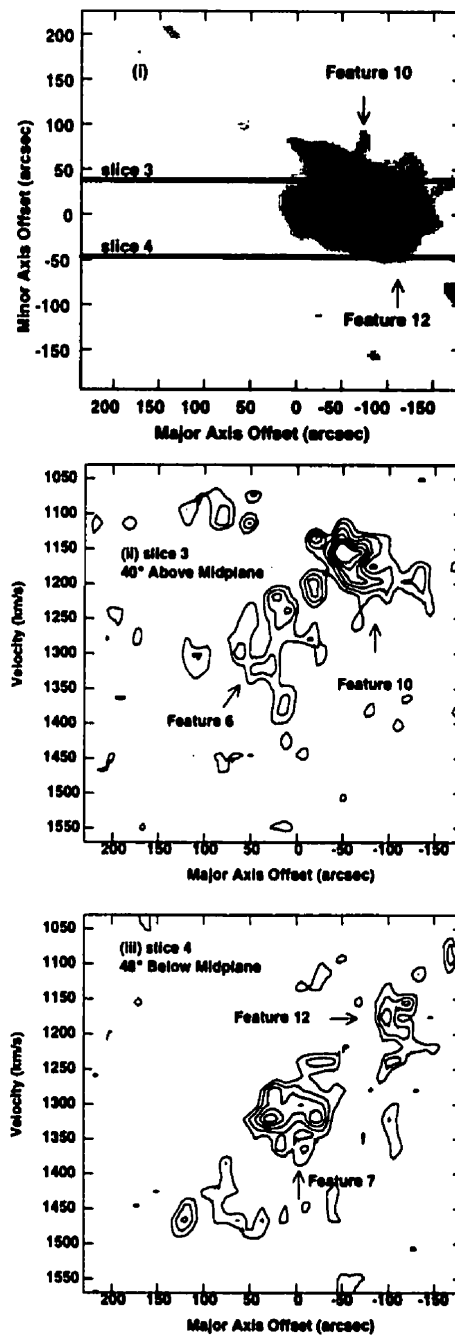


Figure 5.9: Integrated Intensity and P-V Diagrams for Features 10 and 12 in NGC 3044

As in Figure 5.8 but for Feature 10 and 12. In (ii), the uncertain velocity signature of F6 is pointed out but the total intensity map for F6 is not shown (but see Figure 5.6)

formed by a blast at the centres and have ploughed up gas into expanding shells. F10 and F12 do not appear circular in the integrated intensity maps. F10 is probably an expanding shell embedded in a generally disturbed complex at high latitude, causing confusion in identifying its true shape. F12 looks like a spur from the plane of the galaxy but shows expanding shell signature. The smallest velocity range for these four expanding shells is 60 km s^{-1} (not corrected for velocity smearing). Even if we take into account velocity smearing, the velocity range is still large, $\sim 40 \text{ km s}^{-1}$. Because of the fact that these features exhibit clear velocity signatures, we can rule out the possibility that they are 2-dimensional features.

5.3 High Latitude Features in NGC 5775

In NGC 5775, we have identified a total of 6 high-latitude features which are listed in Table 5.2. The analysis presented in this section is new and has not been published. The features in this galaxy are best displayed in the uniform weighting channel map (Figures 5.10 and 5.11). Four of these features show distinct loop appearances in the column density map, they are displayed in Figures 5.12 and 5.13. F1 and F2 are closed and are located at roughly the same projected distances from the galaxy centre (being at $35''.9$ and $48''.4$ along the SE of the major axis, respectively). F3 appears to be an open-topped loop or shell while F4 is also a closed loop. F6 and F4 are likely to be related to the north and south HI bridges connecting NGC 5775 and NGC 5774. F5 does not look like a simple shell or loop but is clearly a distinct high-latitude feature. There is some uncertainty as to the relationship between F1 and F5. While F1 is clearly a loop as seen from Figure 5.12, in channel 1808.5 km s^{-1} it seems to be related to F5. We chose to name them as separate features here based

Table 5.2: High-Latitude Features in NGC 5775

Feature	R. A. h m s	Dec. ° ' "	Velocities km s ⁻¹	No. of Channels	Height from midplane (kpc)
F1	14 51 29.6	3 44 36.0	1683.4 to 1850.2	5	7.1
F2	14 51 27.0	3 43 54.7	1683.4 to 1892.0	6	6.2
F3	14 51 26.8	3 45 53.4	1475.0 to 1683.4	6	7.3
F4	14 51 21.2	3 45 40.7	1475.0 to 1683.4	6	7.9
F5	14 51 32.4	3 43 41.8	1725.1 to 1892.0	5	6.1
F6	14 51 24.5	3 46 37.6	1475.0 to 1600.0	4	4.8

on the integrated intensity map.

We examine the p-v slices at the positions and velocity ranges of the high-latitude features. In Figures 5.14 and 5.15, column density maps and p-v slices of the high-latitude features are shown. The uniform weighting data cube is used in the following analysis because the high-latitude features can more readily be identified. The measured total flux from the uniform map is 14% smaller than the total flux of the natural weighting map. Therefore, the masses measured here will also be lower by the same amount.

High-velocity gas in the directions of many of these high-latitude features is quite obvious and are shown in Figures 5.14 and 5.15. Slices 1 and 3 display the p-v diagrams cut along lines 24" (2.8 kpc) and 40" above the midplane and slices 2 and 4 are cuts 24" and 40" below the midplane. Therefore, features above the midplane will show in both slice 1 and 3 while features below the midplane will show in both slice 2 and 4.

In slice 1, towards the direction of F5, we can clearly see gas moving at velocity

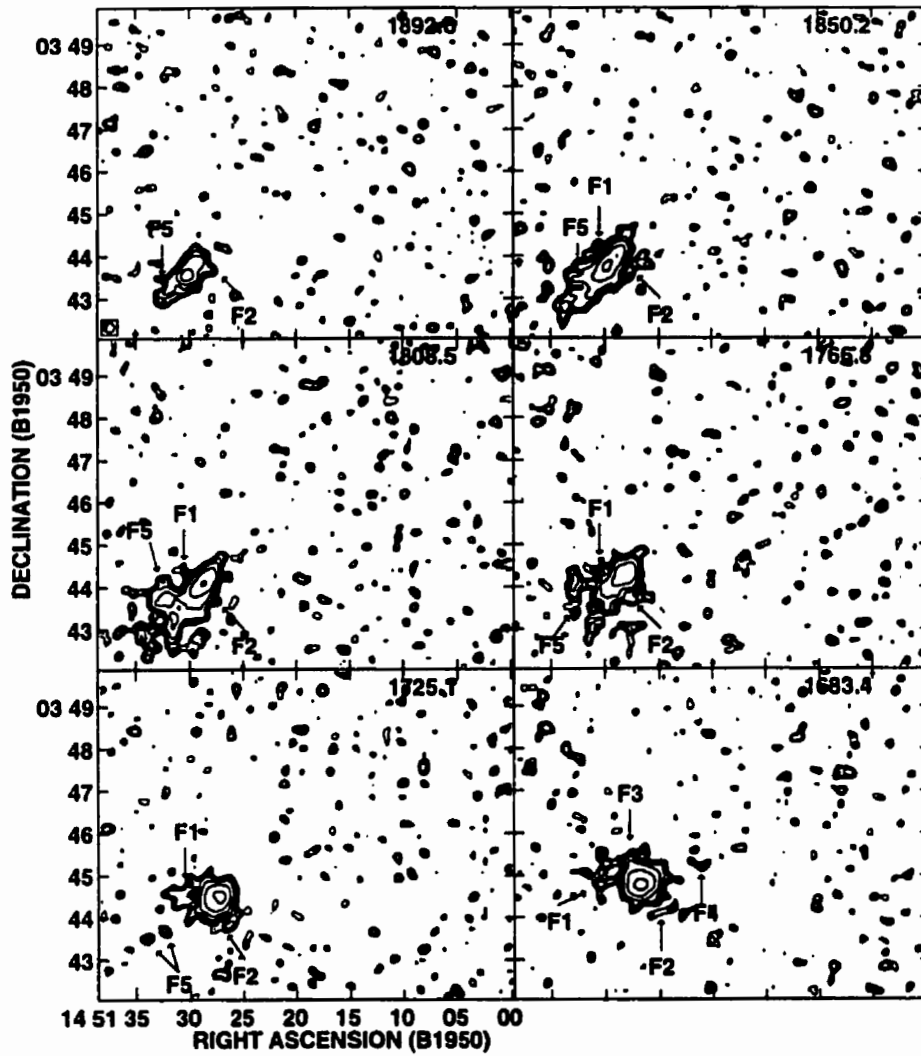


Figure 5.10: Channel Maps Showing High Latitude Features in NGC 5775
The uniformly weighted channel maps showing the identified features. The contour levels are at 1.27(2.5σ), 2.1, 3.2, 5, 8, 11.5 and 15.5 mJy/beam.

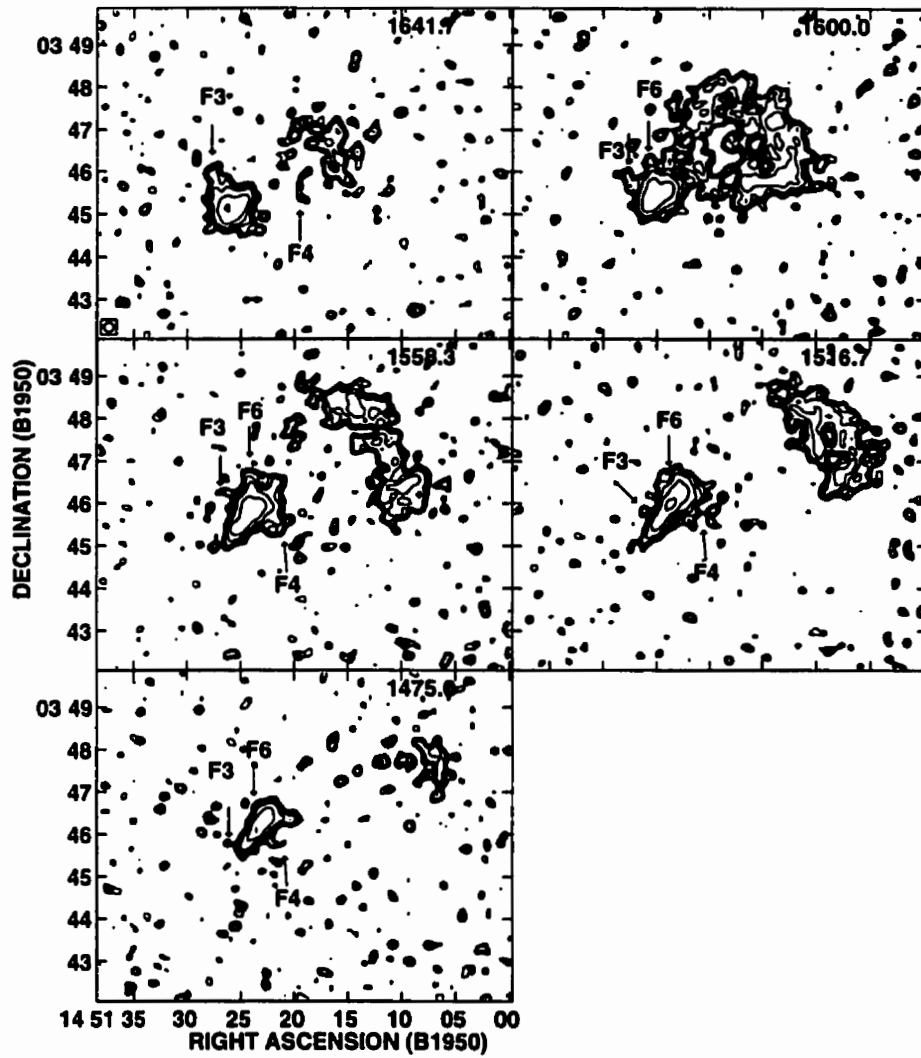


Figure 5.11: More Channel Maps Showing High Latitude Features in NGC 5775
A continuation of Figure 5.10.

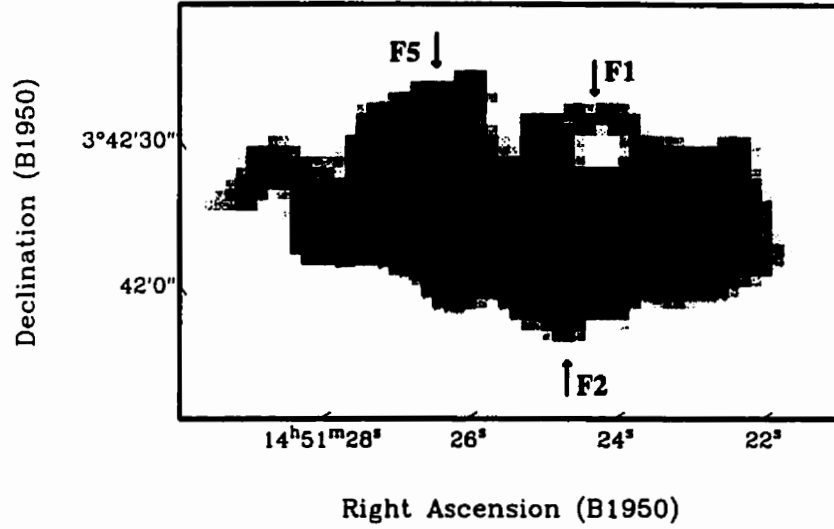


Figure 5.12: Integrated Intensity Map of Features 1, 2 and 5 in NGC 5775. The intensity is integrated over the velocity of 1683.4 km s^{-1} to 1892.0 km s^{-1} . Smoothing and flux cutoff are as in Figure 4.3. The galaxy has been rotated so that the major axis is horizontal.

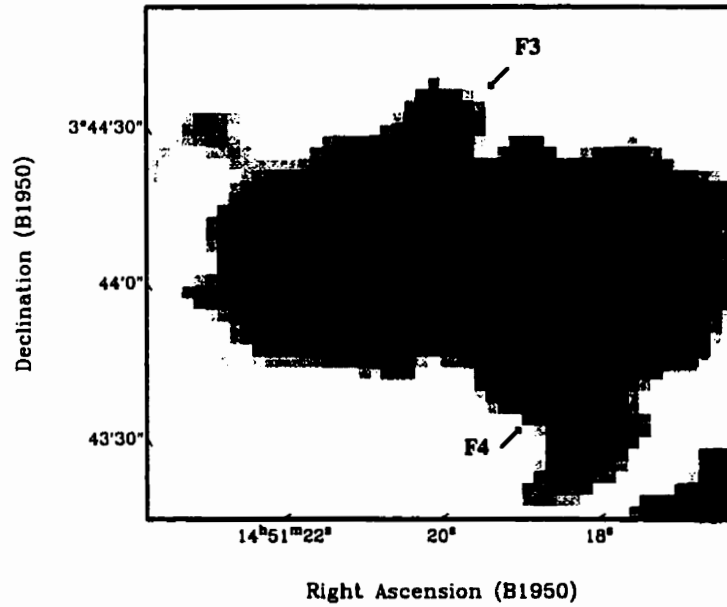


Figure 5.13: Integrated Intensity Map of Feature 3 and 4 in NGC 5775. The intensity is integrated over the velocity of 1475.0 km s^{-1} to 1683.4 km s^{-1} .

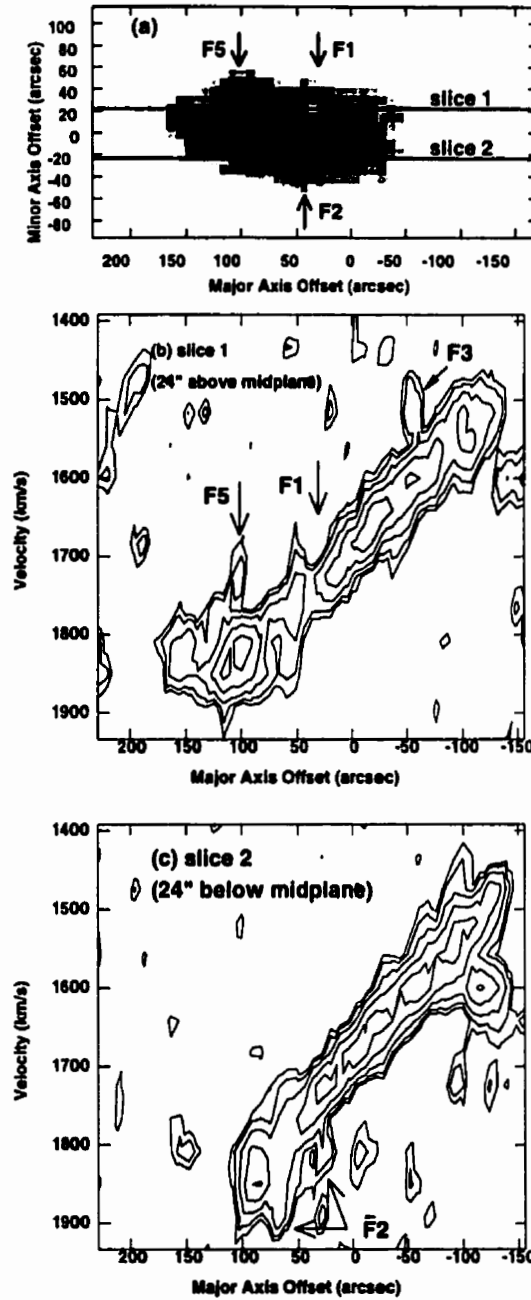


Figure 5.14: Velocities of F1, F2 and F5 in NGC 5775

(a) Uniform weighting column density map showing F1, F2 and F5. Velocity integrated are from 1683 to 1892 km s^{-1} . The two lines labelled slice 1 and 2 show the cuts along which figures (b) and (c) are plotted. (b) p-v diagram along slice 1 (thickness of 8"). Contour levels are at 0.51 (1σ), 0.76, 1.27, 2.1, 3.2, 5, 8, 11.5, 15.5 mJy/beam. (c) As in (b) but for slice 2.

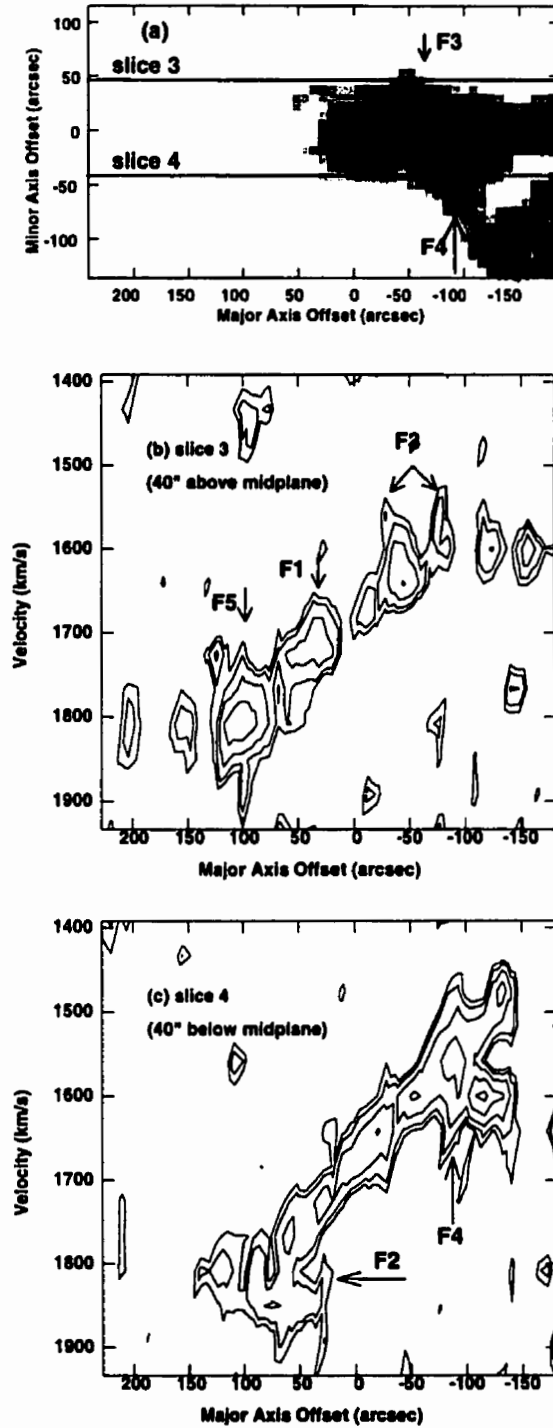


Figure 5.15: Velocities of F3 and F4 in NGC 5775

As in Figure 5.14, but the column density map is obtained by integrating velocity channels from 1475 to 1683 km s^{-1} .

roughly $\pm 100 \text{ km s}^{-1}$ with respect to the velocity of normal disk gas at this radius. This high-velocity gas continues to exist in slice 3, about 2 kpc higher in latitude, at the major axis offset of $100''$. The arrow for F1 in Figure 5.14(b) points to the *centre* of the loop in the integrated intensity map. We can see that in this case, the high-velocity gas seems to exist only in the eastern limb of the loop (at the offset of $50''$ in slice 1). Slice 2 shows high-velocity gas moving away from us on both limbs of F2 (at the offsets of $30''$ and $60''$). This highly red-shifted gas can also be seen in slice 4. F3 is shown in slice 3 with two clumps at the offsets of $-45''$ and $-80''$. These two clumps correspond in position with the two limbs of the loop in the integrated intensity map [Figure 5.15(a)] and show gas moving towards us at velocity higher than expected. F3 also shows up in slice 1, but there the high-velocity gas appears at the centre of F3, in between the two clumps in slice 3. Slice 4 displays high-velocity gas, both red- and blue-shifted with respect to normal disk gas velocity, in the direction of F4. It is also apparent in slice 2 at the offset of $-90''$ (not labelled).

Although high-velocity gas in the directions of these high-latitude features no doubt exists in NGC 5775, there does not seem to be compelling evidence for expansion motion, except possibly for F2 and F3. F3, in particular, shows an interesting variation in velocity structure across the feature. In the lower latitude slice (slice 1), we see high-velocity gas approaching us in the direction of the centre of the loop. If F3 is an expanding shell, we might imagine this gas being the cap of the shell nearest to us. However, we do not see the cap on the other side, moving away from us. This point, though, can be explained if the centre of the shell is at the edge of the disk closest to us, then the expanding gas on the other side of the shell would be ramming into denser gas and decelerating more quickly. In the higher latitude cut (slice 3), the cap is no longer visible, probably due to lower intensity (lesser gas). The two

limbs of the shells appear much stronger due to the fact that there is more gas in our line-of-sight as we look through the thin walls of the shell from the edges. We therefore suggest that the velocity structure of F3 is consistent with that of an expanding shell at the near edge of the HI disk. The other features do not exhibit clear expanding shell signature, yet there is no doubt that they reach high-latitude (a few kpc) and appear as closed loops (except F4). Moreover, the velocity channel maps show that all features apparently change in size over the velocity range in which they can be identified. This shows that these are not static phenomena, and rule out the possibility that they are 2-dimensional features. The integrated intensity map shows very well defined structure, unlike what one might expect if they consisted of gas in turbulent motion with velocity dispersions as high as those seen here. We therefore conclude that the velocity and spatial structures of F2 and F3 in NGC 5775 are most consistent with those of expanding shells.

5.4 Supershell Parameters

Table 5.3 and 5.4 list the masses (M_{sh} , column 2), expansion velocities (V_{sh} , column 3), radii (R_{sh} , column 4), projected galactocentric locations (D_{sh} , column 5), ambient densities in the mid-plane at D_{sh} (n_0 , column 6), kinetic energies ($E_k = \frac{1}{2}M_{sh}V_{sh}^2$, column 7) and kinematical ages (τ_{sh} , column 8) of the expanding shells in NGC 3044 and NGC 5775, respectively. The masses are obtained by summing the fluxes associated with each feature in the velocity channels listed in Table 5.1 and 5.2. These masses are lower limits since parts of the shells are most certainly embedded within the HI disk and are not included. For holes 4 and 7 of NGC 3044, the masses are not listed as the thickness of the shell cannot be determined with confidence. V_{sh} is

Table 5.3: Parameters for Supershells in NGC 3044

Feature	M_{sh} $M_{\odot}$	V_{sh} km s^{-1}	R_{sh} kpc	D_{sh} kpc	n_0 cm^{-3}	E_k ergs	τ_{sh} years	E_E ergs
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
4	...	31.2	1.6	8.9	0.14	...	5.0×10^7	7.3×10^{54}
7	...	31.2	2.3	0.0	0.008	...	7.2×10^7	7.3×10^{53}
10	9.8×10^7	72.8	2.7	8.4	0.16	5.2×10^{54}	3.6×10^7	1.3×10^{56}
12	2.8×10^7	41.6	2.0	13.5	0.03	4.8×10^{53}	4.7×10^7	3.4×10^{54}

taken to be half the total velocity range which again may underestimate the actual range. The combination of lower limits in masses and velocity ranges of the shells results in kinetic energy (E_k) that are strict lower limits too. Radii of the shells are measured from the 1.5σ contours of the p-v diagrams. D_{sh} is an average of the measurements made from the channel maps and the p-v diagrams. We use the modeled density profile in the plane of the galaxy (see column 2 of Table 3.3 for NGC 3044 and Table 4.3 for NGC 5775) to estimate the ambient density at the galactocentric distance of a given shell. The kinematic age of a shell, assuming constant expansion velocity, is $\tau_{sh} = R_{sh}/V_{sh}$. For the supershells listed in Table 5.3 and 5.4, we expect V_{sh} to be underestimated (see above) and therefore τ_{sh} may be overestimated.

The class of models in which supershells are the consequence of the collective action of many supernovae (and stellar winds) is introduced in Chapter 1. In general, numerical simulations produce shells that are smaller and less energetic than the largest supershells observed. Nevertheless, supernovae, being the most energetic events in a galaxy, are most likely the source of energy for these supershells if they

Table 5.4: Parameters for Supershells in NGC 5775

Feature	M_{sh} $M_{\odot}$	V_{sh} km s^{-1}	R_{sh} kpc	D_{sh} kpc	n_0 cm^{-3}	E_k ergs	τ_{sh} years	E_E ergs
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
F2	2.4×10^8	104.3	2.0	5.0	0.12	2.6×10^{55}	1.9×10^7	4.2×10^{55}
F3	2.4×10^8	104.3	1.7	7.6	0.06	2.6×10^{55}	1.6×10^7	4.7×10^{55}

are generated internally. In this case, we can estimate the energies that are needed to produce the expanding supershells observed in NGC 3044 and NGC 5775. In Chapter 6, we discuss other possible mechanisms of producing supershells in these two galaxies.

For an expanding shell which is formed from a one-time energy injection, such as from supernovae, and which is now in the radiating phase of its evolution (see §1.3), numerical analysis by Chevalier (1974) shows that the energy injected is given by

$$E_E = 5.3 \times 10^{43} n_0^{1.12} R_{sh}^{3.12} V_{sh}^{1.4} \quad (5.1)$$

where the variables have the same meaning as before (R_{sh} is in pc and V_{sh} in km s^{-1}). Values of E_E for the expanding shells are listed in column 9 of Table 5.3 and 5.4. As shown in these two tables, the energies required to produce these shells are all upwards of 3×10^{53} ergs, the energy above which supershells are defined (Heiles 1979).

Since the input energy requirements for supershells are significant, it is worth considering the errors on E_E . As indicated previously, the measured V_{sh} is a lower limit since complete shells are not observed. Increasing V_{sh} by a factor of 2, for example, would increase E_E by a factor of 2.6. As stated before, V_{sh} is taken to be

one half the difference between the two extreme velocity channels in which a feature can be identified. We now consider by how much will E_E be changed if we instead use the expansion velocity weighted by density. This can be done for F10 and F12 in NGC 3044 because both of these have well-defined expanding shell structures in the p-v diagrams. From Figure 5.8(ii), we identify the total velocity range of F10 (at an offset of $-80''$) at the highest intensity level (second lowest contour) to be 52.4 km s^{-1} . That is, $V_{sh}=26.2 \text{ km s}^{-1}$. This reduces the value of E_E by about 75%. For F12, the highest contour (second lowest contour) at the position of this feature in Figure 5.8(iii) gives a velocity range of 42.1 km s^{-1} . That is, $V_{sh}=21.0 \text{ km s}^{-1}$. This reduces E_E for F12 by 60%. Density-weighted expansion velocities for the other supershells cannot be obtained easily because some of them are holes and others show only one hemisphere. We assume that the differences in E_E for these supershells are of the same magnitude as those of F10 and F12.

If the features are actually located at larger galactocentric distances than the projected radius, D_{sh} , then the ambient densities, n_0 , would be lower than the listed values. In the extreme case, if Feature 10 in NGC 3044, which has the highest n_0 in Table 5.3, actually occurs at the outer radius of the HI disk ($R = 17.9 \text{ kpc}$), then $n_0 = 0.008 \text{ cm}^{-3}$, decreasing E_E by a factor of about 40. However, note that for Feature 10, $E_k = 5.2 \times 10^{54} \text{ ergs}$. This value gives only the kinetic energy of expansion of the feature and thus the input energy must be much higher (i.e. by at least a factor of 10 for an efficiency of 10%). Therefore, E_E for this feature is likely to be within a factor of 2 of the value listed in Table 5. This then implies that Feature 10 is at a position much closer to its projected galactocentric distance than near the edge of the disk.

Given that irregularities in density distribution occur in both galaxies (§3.3.5, Figure 3.9 for NGC 3044 and Irwin 1994 for NGC 5775), there are also possible

variations in n_0 for individual shells. For example, Feature 7 in NGC 3044, with a projected center at the center of the galaxy, is the most extreme example since it could have an energy more than an order of magnitude larger than the Table 5.3 value if n_0 is determined by the fits to the two sides of the galaxy separately, rather than to the galaxy as a whole (Table 3.3). Overall, however, the irregularities in density tend to be within $\sim 30\%$ for NGC 3044 and $\sim 15\%$ for NGC 5775 of the modeled density, introducing similar sized errors into E_E . Most of the assumptions we have made effectively minimize the values of E_E in Table 5.3 and 5.4. We conclude that the energy estimates, under the assumption of instantaneous input, are correct to order of magnitude.

There is certainly some dependence of the required input energy on adopted model. For example, consider a slower, continuous energy injection over a typical cluster ($\approx$ shell) age (several $\times 10^7$ years). The energy required, $E = L \times \tau$ where L is the input power from supernovae and τ is the cluster's lifetime, can be expressed as $E = 5.3 \times 10^{34} R^7 n_0^3$ where R is the radius of the shell in pc and n_0 is the ambient gas density in cm^{-3} (see Vader and Chaboyer 1995 for details, also see Weaver *et al.* 1977 for continuous stellar wind energy input). Using this, we find energies which agree to within a factor of 4 with the tabulated E_E for Features 4 and 10 in NGC 3044, but are at least an order of magnitude lower for the low density features in both galaxies (cf. Vader and Chaboyer 1995). Also, since the supershells have achieved blowout, an understanding of these features would also benefit from numerical hydrodynamical modeling for such conditions (cf. Mac Low, McCray, & Norman 1989). Nevertheless, one cannot escape the fact that some of the observed high latitude features in the two galaxies are supershells which require large input energies to produce. The kinetic energies of expansion, E_k , which are model-independent and essentially assume 100%

input efficiency, are of order $10^{53} - 10^{55}$ ergs and these kinetic energies are underestimated for the reasons outlined above. For a more realistic situation in which the efficiency is 10% or less, the input energies must be at least an order of magnitude larger.

The values given in Table 5.3 and 5.4 can be compared to values obtained for supershells in the Galaxy and other spiral galaxies. Heiles (1979) found Galactic supershells with radii up to 2 kpc and expansion velocities of order 20 km s^{-1} . Their required energies (using the same equation applied here) are an order of magnitude lower. HI supershells in NGC 3079 (Irwin and Seaquist 1990), NGC 4631 (Rand and van der Hulst 1993) and NGC 1313 (Ryder *et al.* 1995) are of comparable sizes, and expansion velocities, although the expansion velocities of F2, F3 and F4 in NGC 5775 are about 50% higher than the supershells in these galaxies. The supershells in these other galaxies need comparable instantaneous energy input ($10^{54} - 10^{55}$ erg) when scaled to $h = 0.75$. The ages of supershells also appear to be quite homogeneous, at a few $\times 10^7$ years, which is also comparable to the lifetime of an OB association.

Chapter 6

Discussion

In Chapters 3, 4 and 5, we presented the results of our studies of the different components of the ISM, and their correlations as well as evidence of HI supershells in NGC 3044 and NGC 5775. It is the first time external supershell galaxies have been studied in so many wavelengths simultaneously to paint a coherent picture of the ISM in these galaxies. In this chapter, we draw from the results of all preceding chapters to arrive at a global view of each galaxy's ISM structure (§6.1). In §6.2, we consider the possible supershell formation mechanisms based on the two currently popular classes of models: massive stars (§6.2.1) and impacting clouds (§6.2.3). Also, with the fact that blow-out supershells indeed exist in these galaxies, we are able to test the ISM model of Norman and Ikeuchi (1989). This is presented in §6.2.2. Finally, we mention the roles that magnetic field and galactic rotation may have in forming these large-scale structures (§6.3).

6.1 The ISM in NGC 3044 and NGC 5775 – Global Views

6.1.1 NGC 3044

A seemingly unremarkable isolated edge-on barred spiral galaxy, NGC 3044 harbours one of the most massive and extended HI high-latitude features known. In addition, it

displays curious (though not uncommon) asymmetry in many frequencies (see §3.8). In summary, the galaxy's HI and radio continuum disks are thick. Its optical and HI distributions are more extended on the receding (SE) side with respect to the kinematic centre of the galaxy. We find the HI mass on the receding side higher by 14% compared to that of the approaching (NW) side. In contrast, the H α and the radio continuum distributions are more extended on the approaching side. The CO distribution shows a gradual decline in integrated intensity on the SE and a sharper drop-off to the NW. The H α image, when smoothed to the resolution of the HI and radio continuum data, shows better global correlation with the latter than with the former. In HI, numerous high-latitude features can be seen. Twelve features which we can identify with confidence are catalogued. The single most massive feature, F10, on the NW side of the galaxy, reaches a height of 8 kpc above the midplane in the column density map. The region surrounding F10 (in projection) appears to be disturbed as well. HI and radio continuum maps display striking correlation between their high-latitude features. There are also hints that high-latitude CO may exist. The smoothed H α image suggests some high-latitude features. These features appear to anti-correlate with F3 and F6 in HI and the corresponding features in the radio continuum.

The Asymmetry in NGC 3044

The global asymmetry in NGC 3044 manifested itself in *many* components of the ISM. What could have caused the asymmetric distribution? We note here that HI asymmetries in field spirals are quite common. For example, at least 50% of 1400 field galaxies were classified as asymmetrical by Richter and Sancisi (1994) if the two horns in their HI global profiles show difference in peak flux of $\gtrsim 20\%$, or the

total flux between the approaching and receding side differ by 45% or more, or the width difference between the two horns is $\gtrsim 50 \text{ km s}^{-1}$. The origin of the asymmetry, however, still eludes us. Zaritsky (1995) finds a possible correlation between HI asymmetries and star formation rates using the set of HI-asymmetric galaxies from Rix and Zaritsky (1995). The higher than normal star formation rates are consistent with the starburst phase expected after a minor merger¹. Zaritsky therefore suggests that past mergers may be the cause of the optical asymmetries in a sample of about 30 galaxies. Wada and Habe (1992) study the effect of a barred potential on the inflows of gas toward nuclei of galaxies. Their 2-D hydrodynamical simulations show that even *weak* barred potentials which may be induced by very minor galaxy-galaxy interactions (such as a glancing interaction) can cause gas to accumulate in the nucleus if the initial gas mass is greater than 10% of the stellar mass. Note that late-type spiral galaxies such as the ones being studied here do not require interaction to induce bar formation or bar instability (Friedli and Benz 1993, Noguchi 1996). Interestingly, Wada and Habe also show that, for a weak barred potential, the inflow of gas is delayed by a few times 10^8 years after the interaction. By this time, the two galaxies involved in the interaction would not be associated as a pair. Could the asymmetry in NGC 3044 be due to a past galaxy-galaxy interaction (be it minor merger or just a close encounter)?

Minor mergers between gas-rich disks and satellite galaxies have been studied extensively via simulations (e.g., Quinn *et al.*, 1993, Mihos and Hernquist, 1994 and Hernquist and Mihos, 1995). In general, the effects on the parent galaxy of assimilating a satellite one tenth its own mass are: 1. massive gas in-flow to the

¹A minor merger is a process whereby a galaxy cannibalizes a much smaller neighbour (usually its satellite galaxy) by tidal stripping.

nucleus causing a brief ($\sim 10^8$ years) starburst phase; 2. heating of the stellar disk (i.e., increase in vertical scale height by a factor of a few); 3. flaring and warping of the stellar disk. In addition, depending on the satellite's initial density, its core may or may not survive the tidal stripping to arrive at the nucleus of the parent. Therefore, an obvious signature that a merger has occurred would be the existence of a double nucleus.

We do not have the necessary data to search for all these effects. The star formation rate can be investigated though. NGC 3044 is classified as infrared-bright based on the IRAS $60\mu m$ flux density (Soifer *et al.* 1987). The massive star formation rate $SFR(M \geq 5M_{\odot})$ of $0.78 M_{\odot}yr^{-1}$ (Table 3.8) is intermediate between that of the Milky Way (0.3 to $0.5 M_{\odot}/yr$ for a supernova rate of 1 every 5 - 80 years), a relatively quiescent spiral galaxy, and for M82 ($2.2 M_{\odot}/yr$), the fiducial starburst galaxy. Coupled with the facts that NGC 3044 is a barred spiral, and that we have found a central concentration of molecular gas in the galaxy, we conclude that there is a possibility that NGC 3044 has had a minor encounter with another galaxy about 10^8 years ago and has just now accumulated gas in its nucleus and at the beginning of the starburst phase. Moreover, numerical simulations (Hernquist and Mihos 1995) show that the response of the gaseous component usually leads the response of the stellar component. Hence the thick HI and radio continuum disk of NGC 3044 may be a sign that its stellar disk is thick too. However, direct observation to search for enhanced stellar disk scale height would be helpful to strengthen the case. Also, numerical simulations would be useful to see if a minor galaxy-galaxy interaction (rather than a merger) can produce global asymmetries in a galaxy such as those seen in the case of NGC 3044.

6.1.2 NGC 5775

This interacting galaxy is shown to have an impressive radio continuum halo (emission out to ~ 15 kpc above midplane) together with a thick radio continuum disk (~ 1.5 kpc). The HI scale height is also large (1.1 kpc), consistent with the radio continuum observations. This thick gaseous disk may be a result of the interaction with NGC 5774. CO observations show that the molecular gas is concentrated at the nucleus with possibly a fast rotating innermost molecular disk. There exist interesting spatial correlations between the distributions in many wavebands. In the disk the best correlation is that between the radio continuum and the $H\alpha$, although part of the reason is that these two observations have the most similar resolution. There are striking spatial correlations of the high latitude features in all wavebands. In the following, we discuss the implication of these correlations on the origin of the supershells.

6.2 Origin of the Supershells

6.2.1 Massive Stars

Let us for now consider the possibility that massive stars have given rise to these supershells. Is our observation consistent with such a premise? The Chimney model of Norman and Ikeuchi (1989) proposes that the HI features are walls of ambient material (gas and dust) swept up by spatially and temporally correlated supernova explosions. Relativistic electrons then funnel through these “Chimneys” to reach the halo. Other models involving massive stars (e.g., Tenorio-Tagle and Bodenheimer 1988 and references therein, Mac Low *et al.* 1989) show that fragmentation will occur in the shell at late times. There is in fact direct observational evidence that such

a process has occurred in NGC 1620 (Vader and Chaboyer, 1995). We shall, in the following, see that our results are at least qualitatively consistent with this picture. In a later subsection, we also assess whether the global ISM of these two galaxies are as predicted by Norman and Ikeuchi for supershell galaxies.

If supernova explosions are the source of energy input, then between ≈ 400 to 70,000 supernovae (using 10^{51} ergs per supernova) are required to produce the shells in NGC 3044 and NGC 5775, assuming 100% efficiency in converting the total initial energy to kinetic energy. Such a high energy requirement for the supershells is difficult to reconcile with input energies typical of Galactic OB associations which contain only a few tens of stars of spectral types B0 and earlier. $H\alpha$ luminosities of bright HII regions in some external galaxies do suggest the existence of “super star clusters” (SSCs) which contain thousands of massive stars (see Heiles 1990). Furthermore, recent data from the Hubble Space Telescope has revealed the existence of SSCs with hundreds to thousands of the most massive, hot stars in starburst galaxies (Conti and Vacca 1994, Meurer *et al.* 1995). A simplistic way of determining if NGC 3044 and NGC 5775 may host such superclusters is to estimate the combined $H\alpha$ luminosity expected from all the supernova progenitors (massive stars) required to produce the observed supershells and compare this value with the *observed* total $H\alpha$ luminosity of the host galaxy. For NGC 3044, a total of 80,000 supernovae are required to produce F4, F7, F10 and F12 and for NGC 5775, about 89,000 supernovae are required to produce F2 and F3. Following Heiles (1990), we assume 7.2×10^{50} ergs of $H\alpha$ radiation per supernova. The expected $H\alpha$ luminosity, over the average lifetime of a cluster or supershell (4×10^7 years for NGC 3044 and 2×10^7 years for NGC 5775), is then 4.6×10^{40} ergs $^{-1}$ for NGC 3044 and 1.0×10^{41} ergs $^{-1}$ for NGC 5775.

Lehnert and Heckman (1995) observed $H\alpha$ emission of a large number of edge-on

spirals in which NGC 3044 and NGC 5775 are included. They find the $(H\alpha+[NII])$ luminosity of $6.92 \times 10^{40} \text{ erg s}^{-1}$ for NGC 3044 and $2.14 \times 10^{41} \text{ erg s}^{-1}$ for NGC 5775, corrected for galactic extinction but not internal dust extinction. Following Kennicutt (1983), we correct the $(H\alpha+[NII])$ luminosity for the contribution of the $[NII]$ emission using the averaged corrections obtained with a sample of late-type spirals, which is 0.75. The internal dust extinction correction is more uncertain and cannot be corrected easily. Kennicutt (1983) used a mean correction factor of 2.8 by comparing the integrated thermal radio fluxes with the $(H\alpha+[NII])$ fluxes of about two dozen galaxies. This is based on the fact that the thermal radio emission can be used to predict the $H\alpha$ fluxes. A median fit through the observed radio/ $H\alpha$ ratios is found to be higher than the predicted ratio by this factor of 2.8 which is attributed to dust extinction. For highly inclined galaxies like the ones in this study, this mean correction is unlikely to be enough. One way of estimating the dust extinction is to use the model for radio emission given in Condon (1992). In this model, the *global* $H\alpha$ and far-infrared luminosities of a normal galaxy can be related through a single parameter, the massive star formation rate (SFR). The SFR based on the far-infrared luminosity is $0.78 M_{\odot}/\text{yr}$ for NGC 3044 and $2.4 M_{\odot}/\text{yr}$ for NGC 5775 (equation 3.24). The relationship between the SFR and the $H\alpha$ luminosity is

$$SFR(M \geq 5M_{\odot}) = 2.3 \times 10^{-42} \frac{L_{H\alpha}}{\text{erg s}^{-1}}, \quad (6.1)$$

which gives $SFR = 0.12 M_{\odot}/\text{yr}$ for NGC 3044 and $0.37 M_{\odot}/\text{yr}$ for NGC 5775. Note that equation 6.1 is actually adopted from Kennicutt (1983) in which the $H\alpha$ luminosity used to derive this relationship has been scaled by the factor of 2.8 mentioned above to correct for internal dust extinction! Thus, if this correction factor is appropriate for the two galaxies here, and if the model of Condon is appropriate,

then we should expect the ratio of SFRs obtained using the two different luminosities to be 2.8. Instead, we find the SFRs differ by a factor of 6.5 for each galaxy using the two methods. The model in Condon (1992), although simple, predicts a number of well established observational results such as the radio luminosity of M82 and, most importantly, reproduces the FIR/radio correlation in galaxies. For the internal dust correction, because of inclination, the scatter in the radio/H α plot is large and so one general dust correction factor cannot be used for all galaxies, especially the edge-on galaxies studied here. We therefore believe that for our edge-on galaxies, a better internal dust correction is probably closer to the factor 6.5. Note that this correction factor is not uncommon for highly inclined galaxies (e.g., Jansen *et al.* 1994, Prada 1996). This then increases the H α luminosity of NGC 3044 to 3.37×10^{41} erg s $^{-1}$ and 1.04×10^{42} erg s $^{-1}$ for NGC 5775.

Comparing these total observed H α luminosities with those expected from the supershells, we find that at least 13% and 10% of all supernovae in the galaxy must be associated with supershell-forming superclusters in NGC 3044 and NGC 5775, respectively. Considering that these values only account for the confirmed expanding supershells and not the presumably stationary shells and those too small to be observed (which will most certainly be more numerous), these fractions are at best very conservative lower limits. Heiles (1990) predicts about half of all Type II supernovae are within large clusters that are able to produce breakthrough supershells (based on Galactic ISM parameters). Therefore, based solely on available power, we conclude that superclusters can exist in these two galaxies and that the supershells can be powered by these superclusters provided the level of star formation remains constant for the last few $\times 10^7$ years. Kennicutt *et al.* (1989) find that the largest OB associations in normal late-type galaxies such as the two studied here contain

about 24,000 stars. So the supershell-forming associations in these two galaxies must be larger than these largest ones by a factor of 2 to 3. This is certainly a worrisome point. Both galaxies are observed to have normal star formation rates for starburst galaxies, and their FIR/radio parameter conform to the correlation found in normal spiral galaxies. Therefore we do not expect unusually large OB associations to exist in them. Thus, other mechanism(s) may be needed to assist in the formation of the largest of the supershells (see §6.3).

We now examine other evidence of the origin of the supershells from massive stars. Take F3 in NGC 5775 as an example. If F3, which has an estimated age of 1.6×10^7 years, is the result of multiple supernova explosions in a massive OB association, the most massive stars in this association, which live roughly 10^7 years (Chiosi *et al.*, 1978) and produce the bulk of the ionizing photons, would have vanished from the OB association. This could explain the relatively low concentration of H α emission in this region. Mac Low, McCray and Norman (1989) perform numerical simulations using a two-dimensional hydrodynamics code to model the evolution of supershells in different (Gaussian and Exponential) density distributions (Galactic parameters are used) in the disk. They find that supershells typically become gravitationally unstable to fragmentation at around a few million years of their evolution. If we scale their model using the ISM parameters (gas density, vertical scale height and star formation rate) from Chapter 4, we can estimate this fragmentation time for F3. We find the onset of fragmentation is 4.2 million years, which is smaller than the age of F3. In fact, the open-topped appearance of F3 is a sign that fragmentation has occurred. Following fragmentation, the clumps, collapsing under gravity, will become dense enough to shield the interior from radiation allowing molecules to form and the clumps to become molecular clouds. These molecular clouds may eventually form

second generation stars or clusters. The $H\alpha$ emission in the supershells may be an indication that star formation has occurred. However, with a seeing of $1''.1$ for the $H\alpha$ image corresponding to a linear dimension of 130 pc, star clusters are not resolved in this image. The suggestive, indeed tantalizing, outer CO contours (Figure 4.23) indicate the possibility of molecular gas in the supershells. There is also an indication that dust [see Figure 4.22(b)] exists in F3, however, the far-infrared data lack the resolution to show the exact position of the dust with respect to the thin shell of F3.

It is tempting to explain the impressive high latitude radio continuum feature associated with F3 to be shock accelerated cosmic rays being funneled through the open-topped of F3 to reach the halo. We must ask whether the cosmic rays can travel 14.5 kpc (the maximum distance from the midplane of the lowest contour in Figure 4.21) during the lifetime of F3. The radio continuum results of Duric *et al.* (1997) suggest that the timescale for the energetic electrons to travel to this height in the halo is comparable ($\sim 10^7$ years) to the age of F3. Hence the high latitude radio continuum feature associated with F3 can have a disk origin.

It appears, from the above, that the general correlations between the many wavebands for F3 is consistent with many predictions of models involving massive stars as the origin. What about the other supershells? For NGC 3044, from Figures 3.22 and 3.25, there appear to be correlations between radio continuum, $H\alpha$ and HI features in the case of F3, F6, and F10. For F6, the radio continuum and the $H\alpha$ counterparts partially coincide with the western limb of the HI feature. Since energetic particles follow magnetic field lines, this correlation is an indication that the magnetic field lines are embedded within the walls of the supershell (see §6.3). As with F3 in NGC 5775, the western limb of F6 in NGC 3044 may have undergone star formation which gives rise to the $H\alpha$ emission. Because of their complex structures, the exact

spatial correlations between F3 and F10 and their radio continuum counterparts are less clear. There appears to be an HI feature wherever a radio continuum feature exists. However, the converse is not true, as there are a number of HI features which do not (at the sensitivity limit of the observations) have corresponding radio continuum features. The CO data is also suggestive in this galaxy, with the lower contours pointing toward a high latitude HI feature east of F10.

For NGC 5775, the molecular gas in the disk show a “pinch” in the intensity contours at the bases of F1 and F2 (Figure 4.23). The CO contours also suggest that there may be molecular gas in the western limb of F1. In the same region, high latitude H α (Figure 4.24) and radio continuum (Figure 4.25) emission can be seen. Disruption of molecular gas by star formation has been invoked to explain the existence of an older and a younger spiral arm in M82 (Shen and Lo, 1995). Possibly the molecular gas in the disk has similarly been photodissociated or simply destroyed by the shocks from the supernovae. Interestingly, the projected galactocentric distances of F1 and F2 are very similar (centred at 3.4 and 5.0 kpc, respectively, or $\lesssim$ one beamwidth apart). It is possible that these two features are related. If an OB association exploded at midplane and if the ambient density in this region is roughly symmetrically distributed with respect to the midplane, then it is conceivable that two shells could be formed on either side of the midplane. We have also found a high latitude dust feature seen in the 12 and 25 μ m bands which has corresponding features in the HI and the radio continuum (this feature is not identified as one of the high latitude feature in our list as it is not obvious in the individual velocity channel maps). This is consistent with Norman and Ikeuchi’s (1989) picture of chimneys. Norman and Ikeuchi (1989) remark that the vertical dust lanes seen in M31 may be portions of chimney walls, and indeed similar dusty structures have been observed in the Milky Way (Koo *et al.*

, 1992) and in NGC 891 (Howk and Savage, 1997). As stated in Howk and Savage (1997), the energetic events that formed the supershells do not necessarily destroy dust grains. In fact, it is likely that the dust grains are swept up into the thin shells along with the neutral gas. Other well-defined supershells do not have corresponding dust features, but this could be due to the poor resolution of the IRAS data.

To summarize, the correlations between the different wavebands for many of the HI high latitude features in both galaxies are consistent with the predictions of models invoking massive stars. In general, the spatial correlations between the HI, radio continuum and $H\alpha$ high-latitude features are weaker in NGC 3044 than in NGC 5775. Nevertheless, the associations between them can not all be coincidences, hence we believe that these emissions are likely to have a common origin and that the massive stars origin models can, at least qualitatively, explain these correlations.

6.2.2 The Chimney Model and the State of the ISM in NGC 3044 and NGC 5775

Norman and Ikeuchi (1989) (referred to as NI hereafter) have presented a model for the structure of the ISM in galaxies which we outlined in §1.3, based on the ISM parameters for the Milky Way Galaxy. NI's model arises because there is growing evidence that the hot gas in the Galaxy may not be as pervasive as was previously thought (i.e., the three-phase model, McKee and Ostriker 1977). The existence of supershells and superbubbles (see Chapter 1) suggests that supernovae are tightly bunched in OB associations, and so too is the hot gas. To recapitulate, NI's model states that the ISM in a galaxy may be in one (or more) of three stages: the three-phase stage, the Chimney stage, and the two-phase stage.

The two- and three-phase models have been widely discussed in the literature

(see the review by Kulkarni and Heiles 1988). Here we summarize the premise of the Chimney stage. The assumptions for the Chimney stage are: 1. supernovae are highly clumped in OB associations and each OB association produces a superbubble; 2. The superbubble, when formed, expands according to standard supernova remnant expansion law with interior cooling; and 3. Hot gas rises through the cavities of the superbubbles (or Chimneys) to reach the halo. The filling factor of the hot gas, Q , produced by *random* supernovae (the premise of the three-phase model) is a parameter that delineates the different stages of the ISM. It is also a function of ambient gas density (n) (see McKee and Ostriker 1977). If $Q = 1$, we have the three-phase ISM. If Q is small, we have the Chimney stage. If superbubbles are not able to blow out of the disk (i.e., the timescale for the superbubble to reach one scale height is longer than the cooling time), we have the two-phase ISM. Because the rate of supernova *within* OB associations is given by the average supernova rate minus the random supernova rate, the supernova clumping factor (ratio of supernova rate within OB associations to the average supernova rate) can be expressed as a function of Q and n . The different ISM stages are plotted in Figure 6.1 which is adapted from NI's figure 1.

NI predict ranges of ambient (volume-averaged) density, relative clumping of supernovae, mass and energy injection rate for a galaxy in the different ISM phases. The two galaxies studied here present good testing grounds for this ISM model because 1) many components of their ISM have been well-studied and compared here and 2) all the high latitude features in Table 5.1 and 5.2 reach a projected height of at least 5 times the HI scale-heights of their respective host galaxy, derived from the models (see Table 3.3 and 4.3). Therefore, *blow out* supershells which facilitate the transport of mass and energy into the halo clearly exist in them. In the following,

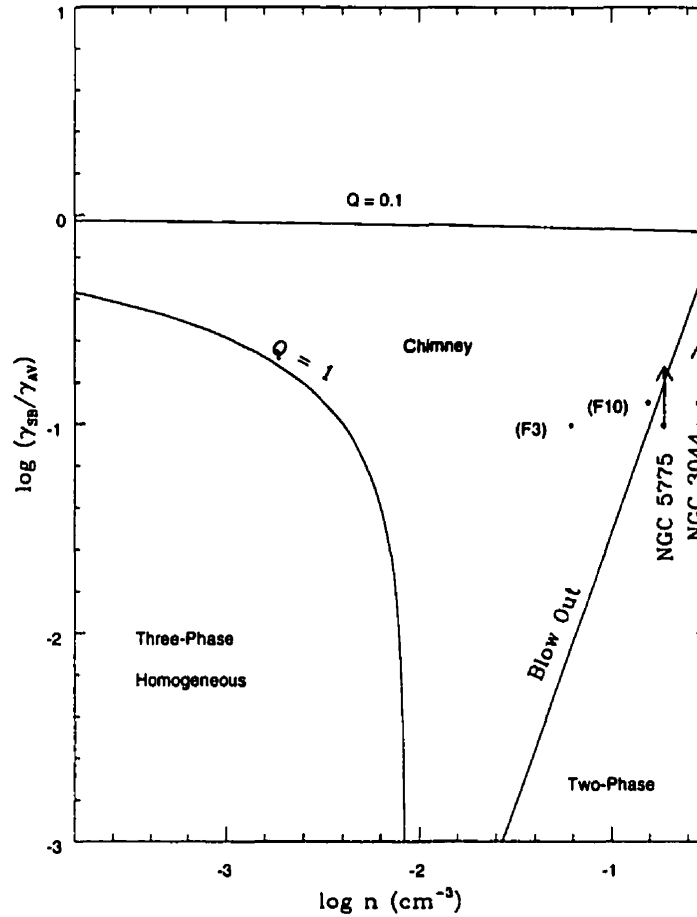


Figure 6.1: Global ISM of NGC 3044 and NGC 5775

Figure 1 in Norman and Ikeuchi (1989) is reproduced here to show the stage of the ISM in NGC 3044 and NGC 5775 (as labelled) predicted by the Chimney Model. The horizontal axis is the ambient gas density and the vertical axis is the supernovae clumping factor (γ_{SB} is the rate of supernovae within superbubbles and γ_{AV} is the average supernova rate). Arrows are to show that these quantities are only constraints and the directions toward the true values. The ISM towards F10 in NGC 3044 and F3 in NGC 5775 are also plotted to show that these regions are in the Chimney stage due to the lower gas density, assuming the supernovae clumping factor does not change.

we either estimate or place constraints on these parameters for the two galaxies to check if they occupy the expected region of parameter space predicted by the ISM picture of NI. Note that NI's model is devised as a model for the Milky Way Galaxy, they therefore use parameters pertaining to the Galaxy whenever necessary. Both our galaxies here are of later Hubble type (SBc compared to Sb for the Milky Way). However, a combination of several factors justify the use of the model as is. One, the values used for such parameters as the supernova rate, ambient gas pressure, supernova scale height, cooling rate, etc. are not accurately determined even for the Galaxy and are only order of magnitude estimates. Two, many of these parameters (e.g., ambient gas pressure, supernova scale height, etc.) are not known for external galaxies, including the two studied here. Three, those parameters that can be estimated for our two galaxies (such as HI scale heights and densities, supernova rates) are shown (see Chapter 3 and 4) to be not too different from the Galactic values. For these reasons, the model of NI is being used here without modification.

The ambient gas density used in NI is the volume-averaged HI density. In the following, the peak HI density obtained from data cube modeling is used as an upper limit for the ambient density for each galaxy. The peak HI density of the neutral component is 0.29 cm^{-3} for NGC 3044 and 0.19 cm^{-3} for NGC 5775 (Table 3.3 and 4.3). From the previous sections, we estimated that the fraction of supernovae locked in supershell-forming OB associations is at least 0.13 for NGC 3044 and 0.10 for NGC 5775. We plot these values for the two galaxies onto NI's Figure 1 (which we reproduced here in Figure 6.1). Since the ambient densities and the supernovae clumping factors are upper and lower limits respectively, we include arrows to indicate this. It can be seen that NI's model comes very close to predicting that the galaxies are both in the Chimney mode. As noted by NI, any one galaxy may be experiencing

a different ISM mode because the supernovae clumping factor and ambient density vary with galactocentric distance. We do not have quantitative distributions of the supernovae clumping factor, but we do have the density distributions for both galaxies. Take for example the HI supershell F10 in NGC 3044. At its projected radius of 8.4 kpc, the HI density is 0.16 cm^{-3} which places this region of the galaxy right in the Chimney phase. Similarly, for F3 of NGC 5775, at its projected distance of 7.6 kpc, the ambient density there is 0.06 cm^{-3} again placing this part of the disk in the Chimney phase. F10 and F3 are also plotted in Figure 6.1.

The mass and energy injection rates together can also define the state of the ISM in NI's model (also see Heckman *et al.* 1993). Strictly speaking (and treated as such in NI), the mass and energy injection of *hot* gas makes the most impact to the halo because the velocity of hot gas of temperature of order 10^7 K is much higher than the velocity of the cold, dense supershells (a few hundreds km s^{-1} compared to a few tens km s^{-1} , NI). We do not have the necessary information to make these estimations. Nevertheless, the fact that the supershells do reach very high latitude, essentially into the halo, and in some cases at high velocities (F2 and F3 in NGC 5775) gives us a lower bound to the mass and energy injection rates.

The total mass of all high latitude features measured is $3.6 \times 10^8 M_{\odot}$ for NGC 3044 and $1.3 \times 10^9 M_{\odot}$ for NGC 5775 (these are lower limits, see Chapter 5) or 7% and 14% of the total HI mass of the respective galaxy. If we assume that 10% of this mass eventually reaches the halo, and the average lifetime for these features is about 4×10^7 years for NGC 3044 and about 2×10^7 years for NGC 5775, then a lower limit to the mass injection rate for cold neutral gas, $\dot{M}$, is $0.9 M_{\odot}/\text{yr}$ (or -0.05 in the Log) for NGC 3044 and $7 M_{\odot}/\text{yr}$ for NGC 5775. For NGC 3044, this mass injection rate is in rough agreement with numerical calculations utilizing the ISM parameters of the

Galaxy ($\dot{M} = 0.33 M_{\odot}/yr$, Heiles 1990). For NGC 5775, however, the mass injection rate is much higher. At least two of its high-latitude features, F4 and F6 are likely to be related to the HI bridge connected to NGC 5774. Even if these two features are excluded in the total high-latitude HI mass, the mass injection rate obtained is still high ($5.5 M_{\odot}/yr$, or 0.74 in log). In order to estimate the energy injection rate for these two galaxies, we assume that the thermal energy released into the halo is about the same as the kinetic energies of the supershells (Tomisaka and Ikeuchi 1987, but note that this is not strictly true for the cooler supershells since radiative losses are important). We again include only the supershells whose expansion velocities are well defined, therefore these values should represent strict lower limits. The total kinetic energies of the supershells are 5.7×10^{54} *ergs* in NGC 3044 and 5.2×10^{55} *ergs* in NGC 5775. These translate to energy injection rates of 4.5×10^{39} *erg s⁻¹* for NGC 3044 and 8.3×10^{40} *erg s⁻¹* for NGC 5775.

We plot the mass and energy injection rates for the two galaxies onto NI's Figure 2 (which we reproduce here as Figure 6.2). Again, the model predicts that the ISM in the two galaxies is on the borderline of the two-phase and the Chimney mode. Due to the way we estimate the energy ejection rates (equal to the kinetic energy), its dependence of the mass (hence mass injection rate) is linear. Therefore an increase in the mass injection rate will drive the two data points toward the upper right but they will never achieve blow out! A more direct mean of estimating the energy injection rate is needed to eliminate this dependence. As mentioned before, the hot component is the appropriate medium for obtaining the injection rate.

Overall, NI's model of the ISM comes close to predicting the chimney stage of the global ISM in NGC 3044 and NGC 5775. The existence of the supershells is evidence that at least some regions in the disks of these galaxies are in the Chimney

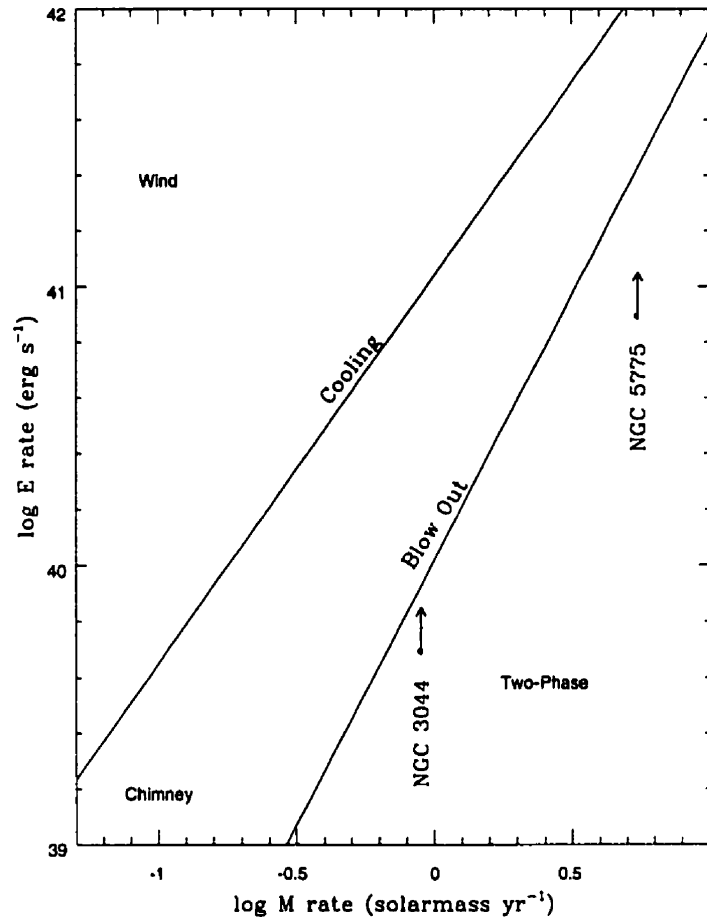


Figure 6.2: The State of the Halo in NGC 3044 and NGC 5775

Figure 2 in Norman and Ikeuchi (1989) is reproduced here to show the state of the Halo in NGC 3044 and NGC 5775 (as labelled) as predicted by the Chimney Model. The vertical axis is the energy injection rate in erg per second and the horizontal axis is the mass injection rate in $M_{\odot} \text{ yr}^{-1}$.

stage. However, it is not clear whether the mass and energy injection rates are high enough to achieve galactic-scale winds. Radio continuum observations certainly indicate energetic particles exist at very high latitude in both galaxies. $H\alpha$ results from Lehnert and Heckman (1996) suggest that NGC 3044 is not currently experiencing a wind phenomenon (based on the relative “roundness” of the minor axis $H\alpha$ contours compared to that of the underlying background brightness contours); this particular parameter is not available for NGC 5775. Other diagnostics such as the high latitude $H\alpha$ emission gas are characterized by shocked and photoionized gas; and the very high electron pressures at high latitude in both galaxies (about 2 orders of magnitude higher than that in the solar neighbourhood), suggest that the halos of these two galaxies do harbour hot gas, although a large-scale wind like that in M82 has probably not developed.

6.2.3 Impacting Clouds

Since the energy requirement are very high, however, the leading alternative scenario, i.e. that the supershells are produced from impacting external clouds, should also be considered.

Impacting cloud models are an attractive way to explain large, energetic supershells because the resulting energies are a function of the infalling mass for which there are no hard limits in the case of galaxy-galaxy interactions. If we assume that the supershells in NGC 3044 are due to impacting clouds, however, we must consider where such clouds would originate. NGC 3044 has no nearby companion, nor is there strong evidence (apart from the asymmetry) for a recent interaction. Moreover, a previous interaction, if it occurred, more likely occurred over timescales of order 10^8 yr (a typical interaction timescale, see also §6.1.1). However, we find kinematical ages

for the shells of a few $\times 10^7$ yrs. Therefore, if the shells are produced by infalling clouds, the situation is more likely one in which high velocity clouds (HVCs) exist around the galaxy and are continuously “raining down”. This also suggests that there should be evidence for such clouds around the galaxy now.

One of the two supershells found in NGC 4631 (Rand and van der Hulst 1993) was modeled by Rand and Stone (1996) as a HVC impact structure using a 3-D hydrodynamical simulation. They found the most likely HVC that formed the supershell has a radius of 500 pc and an HI mass of $1.2 \times 10^7 M_{\odot}$. Since NGC 3044 and NGC 4631 have remarkably similar kinematics, global HI distribution and shell parameters (see Rand 1994), we can assume that infalling clouds of similar size and mass are required to form the supershells in NGC 3044. Converting these parameters to a column density, we find (within one beam) a value of $N_{HI} = 5.2 \times 10^{20} \text{ cm}^{-2}$, which corresponds to the fifth contour in Figure 3.5. There is clearly no evidence at the present time for such massive clouds in the vicinity of NGC 3044. Thus, the impacting cloud model may be reasonable for interacting galaxies like NGC 4631, but is much less attractive for an isolated system like NGC 3044.

For NGC 5775, one may immediately point the origin of the supershells to its interaction with NGC 5774. Indeed, in §5.3, we pointed out that the high latitude F4 and F6 are very likely associated with the HI bridges connecting the two galaxies. The question is, are all high latitude features due similarly to the interaction? The detection limit of the HI column density is about $1 \times 10^{20} \text{ cm}^{-2}$ at the 3.5σ limit (Irwin, 1994). An impacting external cloud like the one proposed above should have a column density of $5 \times 10^{20} \text{ cm}^{-2}$, which corresponds to the second contour in Figure 4.3. Apart from the HI bridges, there is only one unresolved, isolated HI emission feature at this level and it is at a projected distance of 35 kpc SW from the midplane of NGC 5775

(at $\alpha = 14^h51^m9^s$, $\delta = 3^\circ42'40''$ in Figure 4.3). This clump is not associated with any known galaxy in the group in which NGC 5775 is a member (group 148, see §4.1). It is not apparent that this emission is associated with NGC 5774 either, being about the same projected distance south of NGC 5774 as it is from NGC 5775. Assuming the clump is indeed a candidate collision partner with the galactic disk, we can calculate an order of magnitude energy that would be imparted to the disk when it hit. We first assume that the cloud has initial velocity of zero (making our estimate a lower limit since if the cloud is a fragment of the galaxy's interaction, it would certainly have some initial velocity). Next we obtain the potential energy $[\Phi(z)]$ at a distance z above the galactic plane of NGC 5775 by assuming the isothermal sheet model $[\rho \propto \text{sech}^2(z)]$, where ρ is the mass density in the disk and z is the vertical distance from midplane, see Binney and Tremaine, 1987],

$$\Phi(z) = 2 \times 10^{54} \left(\frac{M_{\text{cloud}}}{2 \times 10^7 M_\odot} \right) \left(\frac{z_o}{700 \text{ pc}} \right)^2 \left(\frac{\rho_o}{0.185 M_\odot \text{pc}^{-3}} \right) \ln \left[\cosh \frac{z}{z_o} \right] \quad (6.2)$$

where the mass of the cloud M_{cloud} is taken to be $2 \times 10^7 M_\odot$; z_o is the scale height of the vertical distribution of stellar mass and ρ_o is the stellar mass density at the midplane. The last two parameters take the Galactic and solar neighbourhood values, respectively; z is the height of the cloud above the midplane, taken to be the projected height of 35 kpc. We can then equate the kinetic energy at the point when the cloud hit the galactic plane ($\frac{1}{2} M_{\text{cloud}} v^2$, where v is the velocity at the point of contact) with the potential energy to obtain the velocity of impact. This gives $v = 66 \text{ km s}^{-1}$. This velocity agrees roughly with the expansion velocities of the supershells observed here, especially since it is a lower limit. Therefore, we cannot rule out the impacting cloud model for this galaxy. On the other hand, the spatial correlation of the high latitude features in so many wavebands is more consistent with the picture of

supershell formation due to massive stars. In addition, F1 and F2 are located almost directly opposite in the northern and southern hemisphere, respectively. Impacting cloud models do not predict the formation of shells in both hemispheres (Tenorio-Tagle and Bodenheimer, 1988 and references therein) unless F1 and F2 are formed by two separate impacts. This would seem to be too much of a coincidence. The massive explosions of a star cluster at the midplane would be more likely to create a pair of features as seen.

6.3 The Effect of Magnetic Field and Galactic Rotation on Supershell Formation

From the previous subsections, we see that both an origin from massive stars as well as cloud collisions have difficulties. The problem with the cloud collision model is one of availability of clouds around NGC 3044. The problem with supershell formation due to massive stars is the need for unusually rich OB associations in both galaxies. Although the required power seems to be adequate globally, no such supergiant OB associations have been observed. Perhaps other mechanisms may be involved in supershell formation. Several recent studies have shown, for example, when magnetic fields are included (not just as a secondary effect) that large shells and blow-out can occur with more modest energy requirements (e.g. Kamaya *et al.* 1996; Frei *et al.* 1997). The idea is that when large-scale magnetic fields parallel to the galactic plane encounter supernova explosions, the magnetic field lines are subjected to a vertical perturbation (perpendicular to the plane) causing the field lines to undulate. This is the so-called *Parker Instability* (Parker 1966). The gas located at the peaks of the now wavy field lines will tend to slide down either side making the top lighter. This

then magnifies the amplitude of the disturbance and increase the buoyancy of the field lines to overcome the magnetic tension force, causing it to rise higher above the disk. As the field lines climb, they drag the partially ionized gas, dust and energetic cosmic rays along with them to high latitude. If the field lines extend into the halo, then we have the case of a blow-out superbubble. Sofue *et al.* (1994), who find that the “magnetic inflation” timescale can be shorter than the timescale for the gas to fall back to the disk, conclude that this mechanism can be used to explain the multitude of dust features observed standing vertically against the disk of NGC 253 (Sofue 1994).

Frei (1997) applies a model which combines the effect of galactic rotation with the large-scale magnetic field to the supershells in NGC 3556 (King and Irwin 1997). In this model, the velocity shear due to differential galactic rotation supplies the energy and the effect of the inflating superbubble is magnified by the Parker Instability of the large-scale magnetic field. The author is able to reproduce the observed kinetic energies of the superbubbles in NGC 3556. He also applies the model to other supershells including F10 in NGC 3044 and concludes that a magnetic field strength of about $8 \mu\text{G}$ is necessary to reproduce the kinetic energy. This field strength is not unreasonable based on the observed $7 \mu\text{G}$ mean field strength in NGC 3044 (Sorathia 1994).

Therefore, more sophisticated models including effects like these may reconcile the energy requirements of supershells with fewer number of supernovae.

Chapter 7

Conclusions and Future Directions

7.1 Conclusions

In this work, we have studied many components of the interstellar medium (ISM) in the two edge-on, starburst spiral galaxies, NGC 3044 and NGC 5775. These two galaxies are shown to host large-scale expanding HI supershells. It is the first time that the ISMs of supershell galaxies have been examined in such detailed manner. We have chosen these two galaxies because NGC 3044 is *isolated* while NGC 5775 is an interacting galaxy.

For both galaxies, the global properties obtained from the emission of neutral hydrogen, molecular gas, energetic particles and dust are all normal for galaxies of their morphological class (SBc) and for starburst galaxies. This shows that supershell galaxies are not a “special” class of object.

We examine the possible supershell formation mechanisms based on the two currently popular models: one involving massive stars and the other impacting clouds. For NGC 3044, the impacting cloud models are rejected based on the timescales for shell formation, the absence of companion galaxies, the lack of evidence for surrounding massive clouds and the apparent correlations between the high latitude HI features and features in the radio continuum as well as in $H\alpha$. For NGC 5775, two of the six identified high latitude features may be formed due to the interaction between

it and NGC 5774. However, correlations in many wavebands of three other HI high latitude features are more consistent with a massive stars origin. We propose that for this galaxy, a combination of both mechanisms may be responsible for creating the HI supershells.

Large amount of energy is required to form each of the HI supershells in both galaxies. The energy calculated is equivalent to the energies released by tens of thousands of supernovae, assuming a 100% efficiency for supernovae. Therefore, unusually rich OB associations need to be present in these galaxies at one time in the recent past (a few $\times 10^7$ years). Although super star clusters have been found in some starburst galaxies, the number of massive stars in these clusters still falls short by a factor of a few in order to create the supershells. We suggest that the effects of perturbations in magnetic field lines as well as galactic rotation may play a significant role in supershell formation, thereby reducing the extreme energy requirements.

Finally, Norman and Ikeuchi's (1989) theory of the ISM (the Chimney Model) is tested here for external galaxies for the first time. It is reasonably successful, given the lower limits, in predicting the Chimney stage which these two galaxies are in (since they harbour blow-out supershells). This indicates that the Chimney Model is applicable to late-type starburst galaxies, in addition to the quiescent Milky Way Galaxy. The picture of a global recycling process of the ISM is therefore a good description of the ISM of most types of spiral galaxies.

7.2 Future Directions

Many of the observed parameters, including those used to compare with NI's model, are merely constraints (lower limits). Much can be done in the future to improve this

situation. The following lists a few examples that come to mind:

- CO observations in the disk as well as at high galactic latitudes in both galaxies will be very useful to provide information on the state of the gas in the supershells, i.e., whether molecular gas exists in them. If so, the masses of the supershells would have to be revised upward, implying higher mass and momentum injection rates into the halo. In addition, high latitude CO would strengthen the case for molecular outflow in NGC 5775. High resolution interferometric data will clarify the existence of a fast rotating disk in the inner 1 kpc radius of this galaxy.
- High-resolution far-infrared observations to obtain detailed dust features will help to clarify the correlation between the high latitude HI features with dust.
- Polarization measurements of magnetic field orientation in the galaxies will help to see if some form of magnetic instability (e.g., Parker instability) might provide some assistance to the formation of supershells, thereby alleviating the strained requirement of unusually large OB associations.
- X-ray observations will provide information about the flux and the pervasiveness of the hot gas in the disk and the halo.
- Perhaps most importantly, a comprehensive study of all the supershell galaxies should be undertaken to see if these galaxies, as a class, are in any way(s) different from galaxies not hosting supershells.
- The existence of supershells which require the input energies of tens of thousands of supernovae shows the dynamical nature of the ISM in spiral galaxies.

No doubt their formation mechanism(s), and indeed the evolution of the supershells themselves, have a profound impact on the evolution of the host galaxy as a whole. We have shown here that for the supershells in NGC 3044, supershell formation due to massive stars is the only viable one since the source of impacting clouds does not exist. For many of the supershells (or high latitude features) in both galaxies, observations in many wavebands are correlated and such correlations are consistent with the supershells resulting from spatially and temporally correlated supernova explosions.

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Appendix A

Radio Interferometer

A radio interferometer is a network of two or more antennae working simultaneously in order to obtain a three-dimensional (two spatial dimensions plus the velocity information) image of the source of interest. Each pair of antennae is connected to a correlator which is the spectrometer. The output of the correlator consist of amplitude (power spectrum) and phase difference (provides spatial information) and is represented by complex numbers. Phase differences can be obtained because wavefronts from a point source located away from the telescope pointing centre (the direction where the antennae are pointing) take different times to reach the two antennae, causing the signals from the two antennae to interfere at the correlator. How much the phase differs depends on the orientation and distance between the two antennae as seen by the source. The latter is called the *baseline* and it changes with time as the earth rotates. Since we know the exact locations of the antennae on the ground, and the position of the source in the sky, we can calculate the source's projected distance from the pointing centre in order to produce the observed phase difference. An extended source can be approximated by a great many point sources, hence the distribution of the extended source can be obtained.

As mentioned before, the outputs from the correlators are amplitudes and phases for different baselines at different times. This set of data is called *visibilities* and is

plotted on the “uv-plane” $[V(u, v)]$, which is just the coordinates as seen from the source, hence perpendicular to the direction of the source. The relation between visibilities and the source intensity $[I(\theta, \phi)]$, where θ and ϕ are the E-W and N-S sky offsets from the pointing centre] is that they are a Fourier transform pair. In practice, however, we are not able to fully sample the uv-plane due to gaps between antennae. As a result, when we perform the Fourier transform to recover the source intensities, what we get is a *dirty image*. It can be shown that the dirty image is just the convolution of the *dirty beam* and the source intensities distribution, where the dirty beam is the Fourier transform of the antennae distribution on the uv-plane. Therefore, by applying a deconvolution algorithm, the true source distribution can be recovered (see the next section).

A.1 Standard HI Data Reduction

Data reductions of VLA observations are typically done using AIPS distributed by NRAO. The central 75% of all the visibilities are averaged and contained in the channel zero file. This file is therefore a good representation of the quality of the data and can be used to speed up the editing and calibration processes. Editing and calibration are done on the channel zero files and the subroutines in AIPS used for these tasks generate “tables” which contain the relevant information and are attached to the file as extensions. These tables can subsequently be used on the full set of data.

The first step of data reduction was to look for bad data points and remove them before any calibration can be done. The flux densities of the primary and secondary calibrators are then calculated using respectively the subroutines SETJY and GETJY in AIPS. The antenna gain and phase (i.e., observed visibilities divided by the known

intensities of the calibrators) solutions were calculated for all calibrators using the task, VLACALIB. It is important to ensure that the antenna gain and phase are stable for all antennae throughout. For our data, variations of less than 4% and 2° are achieved for the gain and phase, respectively. When this was done, the task VLACLCAL was used to interpolate the gain and phase for the on source time ranges. Linear interpolation was used. Bandpass calibration was done using the primary flux calibrator as its flux density is usually very strong. This is to correct for variation in gain as a function of frequency. All the above processes were then applied to the full data set (63 frequency channels in total) to obtain the calibrated data cube for the target source.

Next the deconvolution subroutine MX is applied using the Clean algorithm (Clark 1980) discuss below. The Clean algorithm finds the brightest point source, convolves it with the dirty beam to obtain the dirty image of this point source, then subtracts the dirty image from the map, removing all the sidelobes due to this point source. The routine then repeats itself for the next brightest point source and so on, until a pre-defined intensity limit is reached. During the process, the routine keeps a record of the positions and intensities of all the point sources removed. These are then added back to the map and convolve with a “clean beam” (dirty beam with no sidelobes) to obtain the “cleaned image”. There are different ways of giving weights to the visibilities. Natural weighting gives equal weighting to all visibilities. Since there are more visibilities at smaller baselines as the earth rotates, and since smaller baselines are more sensitive to larger structures, natural weighting therefore results in higher sensitivity and lower angular resolution. Uniform weighting, on the other hand, gives equal weight per unit area on the uv-plane. This effectively increases the weight of the visibilities at large baselines compared to the natural weighting case, hence uniform

weighting results in lower sensitivity but higher angular resolution.

Finally, because field-of-view of the telescope is large ($31'.5$), the sensitivity of the outer region of the beam is lower. This primary beam attenuation was corrected with the task PBCOR.

Appendix B

CO Spectral Calibration

The output intensity of a submillimetre telescope is in the form of an *antenna temperature*, T_A^* . The task is to recover the radiation temperature of the source (T_R). T_R is defined as

$$T_R(\nu) = \frac{c^2}{2k\nu^2} (I_\nu - I_{2.7}), \quad (\text{B.1})$$

where ν is the observed frequency, c is the speed of light, k is Boltzmann constant, I_ν and $I_{2.7}$ are respectively the specific intensities from the source and from the cosmic background. To do this, various losses, including ohmic, atmospheric and spillover and scattering losses, have to be accounted for. Ohmic (or resistive) losses are due to the heating of the antenna. Atmospheric losses are due to the absorption of the incoming radiation by the atmosphere as well as the short term fluctuation in the atmosphere. The spillover and scattering losses are caused by the secondary reflector and the telescope support structures. In addition, the actual coupling of the source size (represented by the source coupling efficiency, η_c) to the diffraction beam also has to be taken into account, especially if the source size is a good fraction of the diffraction beam, which is usually taken to be the size of the full moon (but see below for an alternate definition).

The ohmic losses are accounted for by the *radiation efficiency*, η_R , which is given

by

$$\eta_R = \frac{G_0 \omega_A}{4\pi}, \quad (\text{B.2})$$

where G_0 is the antenna gain, or a measure of the fraction of on-axis radiation intensity compared with the average radiation intensity; and ω_A is the *beam solid angle*.

The spillover and scattering losses have two components: the forward and the rearward components (fss and rss , respectively). The rss component is accounted for by the calibration procedure (see below) while the fss efficiency is measured by observing the brightness temperature of the moon.

The atmospheric losses are accounted for by the calibration procedure described here. The antenna temperature of the source is given by

$$T_A^* = \frac{T_A^{on} - T_A^{off}}{G_s \eta_{tel} \eta_{sky}}, \quad (\text{B.3})$$

where T_A^{on} and T_A^{off} are the antenna temperature on and off source, respectively. G_s is the normalized signal sideband gain (usually ~ 0.5), η_{tel} and η_{sky} refer to the fraction of incoming radiation that is actually transmitted to the detector. η_{tel} needs to be determined only once at a given frequency while η_{sky} requires constant monitoring as sky conditions change on short timescale. These two factors are obtained using

$$\eta_{sky} = \frac{\eta_{tel} T_{atm} - T_A^{sky} + T_{Ptel}(1 - \eta_{tel})}{\eta_{tel} T_{atm}}, \quad (\text{B.4})$$

where T_{atm} and T_{Ptel} are the physical temperatures of the atmosphere and telescope, respectively and are assumed to be equal to the ambient temperature, T_{amb} . In order to measure η_{tel} , the telescope is made to point at the sky at different zenith angle to obtain a series of values for T_A^{sky} and η_{sky} . A non-linear least square fit is then applied to find η_{tel} . This routine is termed *sky dip*.

T_A^{sky} is the antenna temperature of blank sky and is obtained using the *three-load calibration* procedure. Three-load calibration refers to the calibration process where

two loads of known temperatures are introduced in the receiver besides the sky. One of which is at ambient temperature, T_{amb} , and the other at the temperature of liquid nitrogen, T_{cold} . The measured voltages of these two loads are

$$V_{amb} = g(T_{rec} + T_{amb}) \quad (B.5)$$

and

$$V_{cold} = g(T_{rec} + T_{cold}), \quad (B.6)$$

where g is the sum of the receiver gains in the image and signal sidebands and T_{rec} is the receiver temperature. From these two equations, we obtain

$$T_{rec} = \frac{V_{cold}T_{amb} - V_{amb}T_{cold}}{V_{amb} - V_{cold}} \quad (B.7)$$

and

$$g = \frac{V_{amb} - V_{cold}}{T_{amb} - T_{cold}}. \quad (B.8)$$

When the telescope points at the blank sky, the measured voltage is, following equation (B.6),

$$V_{sky} = g(T_{rec} + T_A^{sky}), \quad (B.9)$$

so T_A^{sky} can then be obtained from the above equation.

At the JCMT, instead of using equation B.3, a normalized spectrum, S_N , is defined,

$$S_N = \frac{T_A^{on} - T_A^{off}}{T_A^{off}}. \quad (B.10)$$

But $T_A^{off} = T_A^{sky} + T_{rec}$ and $T_A^{on} = (T_A^{sky} + G_s \eta_{tel} \eta_{sky} T_A^*) + T_{rec}$, so we can write

$$S_N \left(\frac{T_A^{sky} + T_{rec}}{G_s \eta_{tel} \eta_{sky}} \right) = T_A^*, \quad (B.11)$$

or

$$S_N T_{sys} = T_A^*, \quad (B.12)$$

where T_{sys} is the *System Temperature* and is defined to be the quantity in the bracket.

The antenna temperature, T_A^* , obtained from equation (B.12) is then the temperature corrected for all losses except for η_c , the coupling term, which is generally unknown. That is, T_A^* is related to the radiation temperature of the source by

$$T_A^* = \eta_c T_R. \quad (\text{B.13})$$

For extragalactic sources, the usual practice is to define the source coupling efficiency with respect to the *main beam* instead of the diffraction beam because the main beam solid angle more closely matches the solid angle of the source. In this case, the *main beam temperature*, T_{mb} , is the desired temperature and is defined as

$$T_{mb} = \frac{T_A^*}{\eta_{mb}}, \quad (\text{B.14})$$

where η_{mb} is the main beam efficiency measured using either Mars or Jupiter.

Appendix C

The Large Velocity Gradient Model

Observations of molecular line transitions from clouds potentially yield a large amount of information regarding the physical conditions in the clouds. Quantities like column densities, excitation temperatures, optical depths, molecular abundances, etc. are crucial to the understanding of physical processes associated with star formation. We now define some of these parameters before proceeding.

The *Optical Depth*, τ_ν , is a measure of the absorption of radiation in a particular wavelength, ν , as it passes through a non-emitting cloud. It is defined by

$$I_\nu = I_o e^{-\tau_\nu}, \quad (\text{C.1})$$

where I_ν and I_o are the emergent and incident specific intensity. When $\tau \ll 1$, the cloud is said to be *optically thin* and when $\tau \gg 1$, it is *optically thick*.

If the radiation passes through a cloud which itself also emits, then the emergent radiation is calculated with the *Equation of Transfer*, given by

$$\frac{dI_\nu}{d\tau_\nu} + I_\nu = S_\nu, \quad (\text{C.2})$$

where S_ν is the *source function* and is the ratio of the emission property (called emissivity) and the absorption property of the cloud.

The *Kinetic Temperature* is the temperature contained in the Maxwell-Boltzmann distribution.

The *Excitation Temperature* is the temperature which governs the relative populations of the different rotational sub-levels of a molecule in the cloud and is defined by

$$\frac{n_j}{n_i} = \exp\left(-\frac{h\nu}{T_{ex}}\right), \quad (\text{C.3})$$

where n_j and n_i are the relative populations per degenerate sublevel, and h is the Planck's constant.

The *Radiation Temperature* is the physical temperature of the cloud and is defined in terms of the source properties as

$$T_R(\nu) = \frac{h\nu}{k} \left(\frac{1}{e^{h\nu/kT_{ex}} - 1} - \frac{1}{e^{h\nu/kT_{bg}} - 1} \right) (1 - e^{-\tau_\nu}), \quad (\text{C.4})$$

where T_{bg} is the temperature of the cosmic background radiation and k is the Boltzmann constant.

The observed intensity of a molecular line can be an extremely complicated functions involving many free parameters (e.g., gas densities, molecular abundances, kinetic temperatures, etc.). For example, when the opacity of a molecular transition is of order unity, photons will be trapped within the cloud and contributes to the excitation of that transition. This means that the equations of radiative transfer and the equations of statistical equilibrium (see below) must be solved simultaneously in order to obtain the level populations of the molecule in question. One widely employed method for determining physical quantities in clouds is the “Large-Velocity-Gradient” approximation. It was proposed by Sobolev (1960) and was applied to the interstellar medium by Goldreich and Kwan (1974).

The LVG approximation can be applied to clouds because many observed molecular lines have much larger line width than typical thermal line widths ($\sim 0.2 \text{ km s}^{-1}$). Goldreich and Kwan proposed that these broad lines are due to large-scale gravitational collapse of the clouds. It is then possible to assume that the velocity gradient of the cloud is large and that any photon, if not re-absorbed at the vicinity of the point of emission, will be able to escape the cloud. In other words,

$$\frac{\Delta l}{l} = \frac{\Delta V_{th}}{V} \ll 1 \quad (\text{C.5})$$

where Δl = distance from the point of origin over which a photon has a chance of being absorbed; ΔV_{th} = the local thermal line width; l and V = typical systematic length scales and velocity, respectively, in the cloud.

Sobolev has shown that the value of the mean intensity J_ν at any point in the cloud can be determined by the local conditions, i.e.,

$$J_\nu = (1 - \beta) S_\nu \quad (\text{C.6})$$

where S_ν = the local source function and β = photon escape probability.

For homogeneous and isotropic collapse,

$$\beta = \frac{1 - e^{-\tau}}{\tau}. \quad (\text{C.7})$$

We can express the equations of statistical equilibrium,

$$\frac{\partial n_j}{\partial t} = \left(\frac{\partial n_j}{\partial t}\right)_{rad} + \left(\frac{\partial n_j}{\partial t}\right)_{coll} = 0, \quad (\text{C.8})$$

in terms of the level populations n_j and a number of free parameters.

The radiative term is given by

$$\begin{aligned} \left(\frac{\partial n_j}{\partial t}\right)_{rad} = & \frac{g_k}{g_j} A_{kj} \left(n_k + \frac{c^2}{2h\nu_2^3} n_k J_{\nu_2} - \frac{c^2}{2h\nu_2^3} n_j J_{\nu_2} \right) - \\ & A_{ji} \left(n_j + \frac{c^2}{2h\nu_1^3} n_j J_{\nu_1} - \frac{c^2}{2h\nu_1^3} n_i J_{\nu_1} \right) \end{aligned} \quad (\text{C.9})$$

where level j is $(i+1)$, level k is $(j+1)$, g_i is the statistical weight of level i , A_{kj} is the Einstein coefficient for spontaneous emission from level k to level j and ν_1 is $\nu_{j \rightarrow i}$ and ν_2 is $\nu_{k \rightarrow j}$.

The collision term is given by

$$\begin{aligned} \left(\frac{\partial n_j}{\partial t}\right)_{coll} = & \sum_{L=j+1}^{\infty} \left(\frac{C_{L \rightarrow j}}{g_j}\right) g_L \{n_L - n_j \exp[-\frac{hB}{kT_k}(L(L+1) - j(j+1))]\} + \\ & \sum_{L=0}^{j-1} \left(\frac{C_{j \rightarrow L}}{g_L}\right) g_L \{n_L \exp[-\frac{hB}{kT_k}(j(j+1) - L(L+1))]\} \end{aligned} \quad (C.10)$$

where $\frac{C_{L \rightarrow j}}{g_j}$ = downward collisional rate per magnetic sub-level. Theoretically derived rate constants for individual transitions exist for a number of molecules; B = rotational constant ($\nu_{j+1 \rightarrow j} = 2B(j+1)$)

Note that we consider here only linear molecules with pure rotation spectra.

The values of the mean intensities J_ν in equation C.9 is given by equation C.6. Since the local source function is the ratio of the line opacity κ_ν and the line emission coefficient j_ν , we need to know these two quantities in terms of n_j and the free parameters. These are given by

$$\kappa_\nu = B_{ij} \frac{h\nu}{4\pi} g_i n_i \left(1 - \frac{n_j}{n_i}\right) \phi_\nu X n_{H_2}, \quad (C.11)$$

where ϕ_ν = normalized line profile and X = relative molecular abundance of the molecule with respect to $(H_2 + H_e)$, and

$$j_\nu = A_{ji} \frac{h\nu}{4\pi} g_j n_j \phi_\nu X n_{H_2}, \quad (C.12)$$

so that

$$S_\nu = \frac{2h\nu^3}{c^2} \frac{1}{(n_i/n_j - 1)}. \quad (C.13)$$

β is a function of τ . But $d\tau_\nu = \kappa_\nu dz$ where dz is along the line of sight. For the line profile, we use a block function of height $\frac{1}{\Delta\nu}$ and width $\Delta\nu$, where $\Delta\nu = \frac{\nu}{c} \frac{dv}{dr} dr$ and $\frac{dv}{dr}$ = local velocity gradient.

Then

$$\tau_\nu = \frac{c^3 A_{ji}}{8\pi\nu^3} \frac{g_j n_i}{(dv/dr)} [1 - \exp(-\frac{h\nu}{kT_{ex}})] X n_{H_2}. \quad (C.14)$$

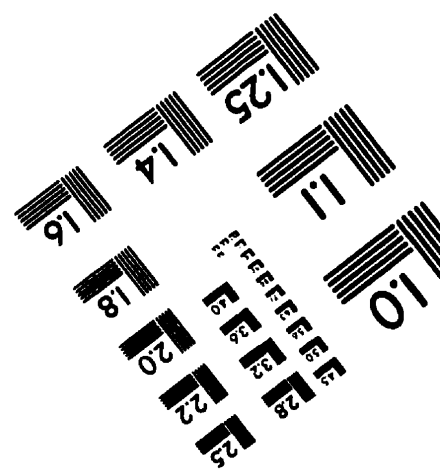
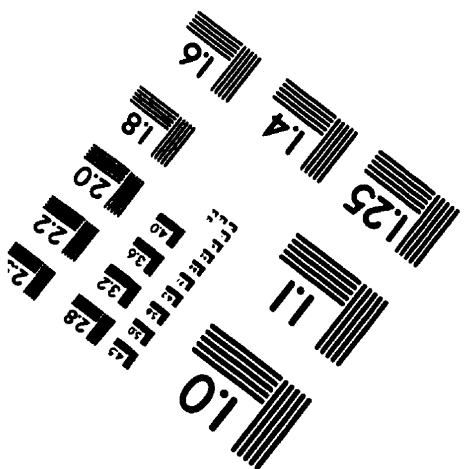
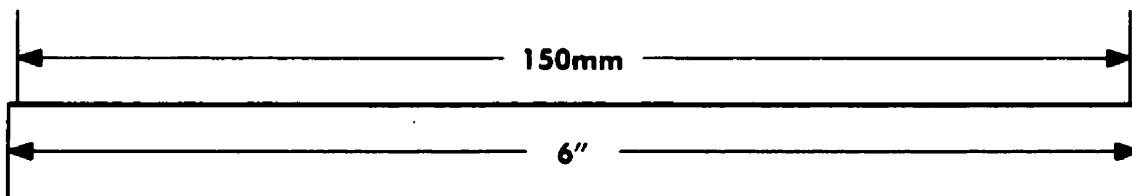
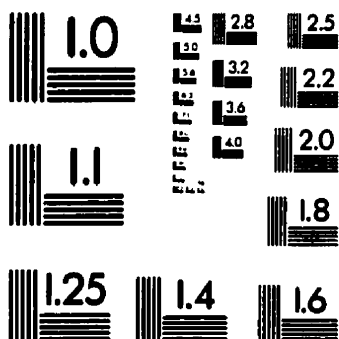
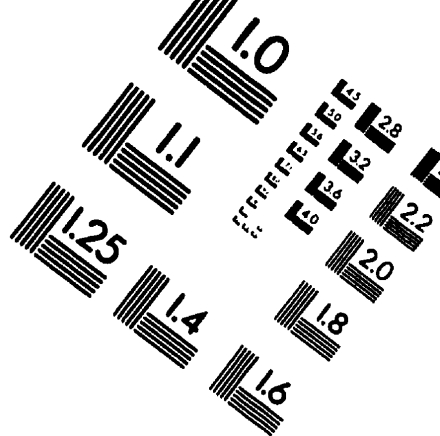
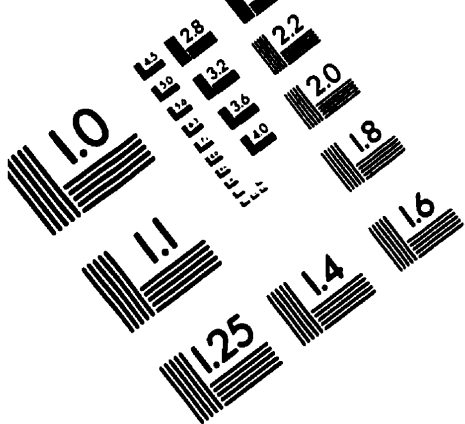
As a result of all the equations above, we obtain a system of non-linear equations in terms of the unknown n_j 's, which can be solved numerically. In practice, it is safe to assume that the level populations are zero above some maximum level, e.g., $J_{max}=10$. Note that the following constraint also has to be satisfied:

$$\sum_{j=0}^{J_{max}} (2j+1)n_j = 1 \quad (C.15)$$

Once we have the level populations, equation C.3 will be used to find T_{ex} and equation C.14 gives the optical depths. The radiation temperature T_R is obtained using equation C.4.

The convolution of T_R with a beam profile will yield predictions of the observable quantity T_R^* .

TEST TARGET (QA-5)



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