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UMI®
Properties of the Molecular Interstellar Medium in the Lenticular Galaxy NGC 5866

Andrew G. LeBlanc

Submitted in partial fulfilment of the requirements for the degree of Master of Science

Saint Mary's University
Halifax, Nova Scotia

September 2001

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Certificate of Examination

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A thesis is a strange thing. It starts off small and slowly becomes bigger. Almost unnoticeably, it grows to unmanageable proportions. Each new piece of information spawns more questions which need to be answered, chapters double in size, direction shifts, and focus becomes lost. At some point it gets tamed and cut back, rearranged and finally crystallizes into what you see before you.

Although from the outset it appears to be the work of a single author, this is hardly the case. Without the help of many people a thesis could never truly be finished. Outside influences are essential to the refinement of the text and the quality of the content. Naturally, in thanking the many people who have helped, the thesis supervisor gets first billing since they are involved from the inception, long before writing can even be considered. Also, most of the responsibility for the above mentioned editing falls into their lap. Dr. Gary Welch has provided consistent encouragement, advice, and insight throughout the entire process and deserves much of the credit. This includes everything from infinite patience during the slow times to resurrecting reference papers which were otherwise impossible to find or oblivious to me. Gary also needs to be included with the faculty thanks since he was a part of all of the soon to be mentioned groups.

The Master of Science in Astronomy programme at SMU covers 17520 hours; many of those hours were spend in the grad office. Peter started the program with me and has played an important role over the last 2 years, since, misery loves company. Any assignment, presentation, project, test or exam I had, so did Peter. Sandro, Trish, JR, Kevin and Dave deserve mention as well. Though they are of differing graduating classes, they shared in many of the late nights/early mornings with Peter and I, both astronomy and beer related (and not to forget Nick when mentioning beer). Many faculty members also enriched my time here. Dr. Turner, Dr. Guenther, Dr. Loken and Dr. Sarty provided me with an excellent education inside and outside the class room. Dr. Butler gave me the opportunity to take on roles of greater responsibility than normally assigned to a grad student at Saint Mary's. One of these was the chance to teach the forensic science class physics labs. These were both interesting and exciting to watch. Dr. Clarke and Dr. Turner, were on my comprehensive exam committee and Dr. Marleau, Dr. Mitchell and Dr. Irwin from Queen's assured that the final version of this thesis met the high standards of the scientific community and that I, too, did the same. Thanks also to Dave and Shawna for ensuring that the computers ran smoothly.

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Thank you to everyone mentioned here and to any I have missed.
The IRAM 30m telescope has been used to observe the J=1-0 transition of $^{12}$CO at several positions along the central dust lane of NGC 5866. The data were used to determine the large-scale properties of the molecular interstellar medium. We find that the interstellar medium mass, $M_{\text{H}_2} = 4.55 \pm 0.43 \times 10^8 \, \text{M}_\odot$, is consistent with simple mass-return calculations from evolved stars (e.g. Faber & Gallagher, 1976). A computer model was employed to constrain the distribution and kinematics of the gas, by attempting to simulate the multi-position spectroscopy. The gas is found to be in a broken Gaussian ring-like distribution with several warmer areas mostly found on the red shifted side. Rotation velocities much higher than those reported for hot the stars and the ionized gas are required to reproduce the observed CO line width. The star formation rate is $\approx 0.05 \, \text{M}_\odot/\text{yr}$ from H$\alpha$ data, about average for an S0 galaxy, suggests that NGC 5866 is in mass balance based on the calculated mass return rate. The origin of the gas is most likely internal. However, the rapid rotation of the gas, a $M_{\text{H}_2}/M_{\text{H}_i} \geq 3.5$, and evidence for a higher star formation rate in the past suggest that the gas might have been perturbed by an outside influence.
Chapter 1

Introduction

1.1 The S0 Galaxy Class

Lenticular (S0) galaxies present interesting laboratories for testing theories of the interstellar medium (ISM), galaxy interaction and galaxy formation. The S0 class of galaxies was not discovered, but first proposed in order to complete Hubble's "tuning fork" diagram, illustrating possible galactic evolution in his landmark book, The Realm of the Nebulae (Hubble, 1936). Hubble's tuning fork diagram, shows a sequence of increasingly elongated ellipticals (E0-E7) ending with the S0 class and then bifurcating into spiral branches showing increasingly extended spiral structure, one with a central bar (SBa-SBc), one without bars (Sa-Sc). When discussing galactic evolution, we interpret the sequence to go from spiral to elliptical, however, ellipticals, S0s and Sas are referred to as early-type galaxies based on Hubble's original suggestion. The formation of S0 galaxies remains a topic of debate. Some believe that later type spirals lose their angular momentum and heat up their stars through interaction with other galaxies or the
intergalactic medium in dense clusters, eventually ending up as an early-type (Spitzer & Baade, 1951, Gunn & Gott, 1972, Icke, 1985, Dressler, 1997). Others argue that a lenticular galaxy can be formed simply by having a normal spiral exhaust its gas supply through star formation (Sandage, Freeman & Stokes, 1970). Either way, the S0 galaxy class is the keystone to the whole evolutionary sequence since lenticulars are regarded as transition objects between the ellipticals and the spirals. After writing The Realm of the Nebulae, Hubble went on to find many examples of the S0 class but did not publish on them specifically (Sandage, Sandage & Kristian, eds., 1975). The first true description of the S0 galaxy class was not published until 1961 in the Hubble Atlas of Galaxies (Sandage, 1961).

Lenticular galaxies get their name from their double convex lens-like appearance. An S0 galaxy seen edge-on has a large bulge and a visible disk with no spiral structure. The class is divided into 3 major subclasses, S01, S02, S03 in order to further illustrate the transition between elliptical and spiral galaxies. The S01 subclass is closest to an elliptical in appearance and is the "earliest" form of S0 galaxy. The S03 subclass is closest to normal spirals, being characterized by the presence of a dust lane within the disk when viewed edge-wise (Sandage, 1961). NGC 5866 is a good example of an S03 galaxy.

1.2 The Lenticular Interstellar Medium

The original opinion concerning lenticular galaxies was that they are dead, in the sense of having no appreciable interstellar medium (ISM) and no longer creating new stars. Faber
& Gallagher (1976) showed in their seminal work that all early-type galaxies should, however, presently have robust ISMs due to mass return from dying stars. Without continuous star formation or some other way of removing gas, an easily detectable ISM should develop in a Hubble time. More recent studies, with more sensitive equipment, have confirmed that, indeed, ellipticals and S0 galaxies do have some form of an ISM in many cases (see Henkel & Wiklind, 1997, for a review of the molecular ISM, Knapp, 1998, for a general overview). However, despite this theoretical prediction and numerous observations, many early-type galaxies show only a sparse ISM or none at all. If all lenticulars have dying stars returning gas, where is this gas going?

Most S0 galaxies are found within dense clusters like the Virgo and Coma clusters of galaxies. Looking back in time at high redshifts shows that the spirals were once more common than they are today, whereas early-types were less common (e.g. Dressler et al., 1997). These two observations have lead many to speculate that early-type galaxies form from spiral galaxies and that the environment must play an important role. Dressler (1980) showed that there is a morphology-density relationship: although all types of galaxies are found in all environments, the number of S0s per unit volume rises with number of galaxies per unit volume. That seems to confirm that at least in some cases, S0s are formed through environmental influences. In high density regions, S0s most likely form from normal spiral galaxies which have their gas removed by interaction with other galaxies or through ram-pressure stripping (Gunn & Gott, 1972) by the hot intergalactic medium (IGM), whose presence in dense galaxy clusters is revealed through its X-ray emission.
Galaxy interaction is a convenient hypothesis since it can also explain why some early-type galaxies have an interstellar medium. A second interaction, after the one which presumably formed the S0 galaxy, provides an accretion source to replenish the lenticular's ISM. Kinematical studies of the gas in S0s suggests that the ISM has been accreted from external sources, at least in some cases (Bertola et al., 1992). The most convincing example of an external origin for gas in an S0 is counter-rotation with respect to the stars, since it is very hard to explain this from an internal origin standpoint (Bertola et al., 1992).

The previously discussed S0 formation theories and ISM evolution scenarios fall short when discussing field S0s since none of the cluster conditions, such as, an intergalactic medium or large local number density of galaxies, exist which could cause a morphological transformation or an ISM exchange. For this reason, field S0s are interesting to study. NGC 5866, the focus of this work, is most likely in a loose group of galaxies but this environment is not comparable to those in the Virgo and Coma clusters due to the lower number density of galaxies and lack of an observed IGM. Could similar mechanisms be effective in such seemingly different environments? This seems doubtful, but there are other ways of removing gas from a galaxy which do not require interaction. Winds from type Ia supernovae have been shown to be effective at removing any gas returned to the ISM from dying stars (Matthews & Baker, 1971). Also, star formation cannot be ruled out in these galaxies. A starburst period can easily deplete much of the gas by converting it into stars and expelling the remaining gas by type II supernovae.
1.3 Motivation

The study of molecular gas in galaxies is important since new stars form out of this cool gas (see Young & Scoville, 1991, for an overview) and also because of a significant fraction of the total ISM might be in molecular form. CO observations provide one of the easiest ways of studying the molecular ISM since many of its rotational transitions are observable in radio wavelengths through the Earth's atmosphere. Studying a galaxy's molecular gas kinematics and distribution provides powerful clues as to how the galaxy formed and what has happened to the galaxy in the past, in terms of interactions and star formation histories.

Shedding light on the competing theories concerning the origin of the ISM in lenticulars and presenting a comprehensive picture of what a typical S0 galaxy is like are the motivation behind a volume limited survey of the cool ISM in S0 galaxies, currently being performed by Welch & Sage (2001). The survey members were chosen based on distances and morphologies published in the Tully (1988) Nearby Galaxies Catalogue. The survey looks for $^{12}$CO in the $J=1$-$0$ and $J=2$-$1$ transitions and also for atomic Hydrogen, HI.

This work presents a study of one of the survey members, NGC 5866, using extensive $^{12}$CO $J=1$-$0$ data from the Institut de Radioastronomie Millimetrique (IRAM) 30m telescope. The goal is to provide a general overview of what the cool interstellar medium is like in NGC 5866. Discussion on the molecular gas mass, and how it compares to
other interstellar matter phases (HI, dust) will be presented along with details of the molecular gas distribution and kinematics gleaned from a simple computer model.

CO has been previously detected in NGC 5866. The central questions of *where did the ISM come from? and where is the gas going?* will be answered through analysis of the above and by comparing the results to published statistics on the S0 class in general in order to present a complete picture of the cool ISM in NGC 5866. In general, ISM origin theories fall into two categories, internal or external. If the gas in NGC 5866 is of internal origin, the gas evolved completely in a "closed box", if its origin is external, the gas was captured from some other source such as a dwarf companion. This is perhaps an oversimplification as there may only be partial stripping in an interaction or simply a perturbation of the gas.

NGC 5866 should have an appreciable ISM based on the simple prediction of Faber & Gallagher (1976). The mass return rate and the accumulated mass of the ISM are found by assuming a planetary nebulae birth rate and mass and scaling by the size of the galaxy, reflected by the galaxy's bolometric luminosity. Integrating over a given time period reveals the predicted ISM mass. The planetary nebula birth rate used is $9.2 \times 10^{-12}$ /yr/Lo(bol) (Peimbert, 1993), and individual planetary nebulae are assumed to have a mass of 0.3 $M_\odot$, which gives a yearly mass loss rate of $2.76 \times 10^{-12}$ $M_\odot$/yr/Lo(bol). The bolometric luminosity of NGC 5866 is $3.77 \times 10^{10}$ $L_\odot$ (bolometric correction from Peimbert, 1993), yielding a mass return rate (MRR) of

$$\text{MRR} = 0.10 \ M_\odot/\text{yr} \quad (1.1)$$
Integrating this value over $10^{10}$ years gives the predicted ISM mass from stellar material returned to interstellar space,

$$M_{\text{ISM}} = 10^9 \, M_\odot$$  \hspace{1cm} (1.2)

The mass given in equation 1.2 is on the order of what any search for an interstellar medium in NGC 5866 should find. Due to the simple nature of this calculation, the mass found here can only be used as a guideline. However, appreciable deviation from this value, either up or down, would indicate an external influence. Other quantities such as the star formation rate and star formation efficiency will be discussed in order to answer the second question.

1.4 NGC 5866

NGC 5866 is an edge-on, S0\(_i\) galaxy at a distance of 15.3 Mpc, located in the NGC 5907 group of galaxies, along with other bright members, NGC 5907 and NGC 5879. The galaxy has a prominent dust lane tilted by $\sim2.5^\circ$ from the optical major axis (Burbidge & Burbidge, 1960, Bertola et al., 1992), and is a strong infrared emitter having been detected by the Infrared Astronomical Satellite (IRAS). The Röntgen Satellite (ROSAT) X-ray observatory satellite found X-ray emission from NGC 5866 with a X-ray luminosity of $\sim2.8 \times 10^{40}$ erg/s in the 0.1-2 keV band (Pellegrini, 1994). CO was first detected in NGC 5866 by Thronson et al. (1989) and Wiklind & Henkel (1989). Wiklind & Henkel (1989) reported on the first partial mapping of the CO in this galaxy and found that the CO followed the optical dust lane but did not publish their map. Previous studies give estimates of the $H_2$ mass from CO data in the range of $\sim10^8$ solar masses, $M_\odot$, (Wiklind & Henkel, 1989, Thronson et al., 1989, Young et al., 1995, Taniguchi et
al., 1994) but no positive detection of HI has been made. The upper limits on 21 cm emission give an atomic Hydrogen mass of no more than \( \sim 10^8 \) M\( \odot \) (e.g. Gallagher, Faber & Balick 1975, Knapp & Gunn, 1982, Balkowski & Chamaraux, 1983 Haynes et al., 1990). From [C II] (158 \( \mu \)m) and [O I] (63 \( \mu \)m) emission lines, Malhotra et al. (2000) find that the ultraviolet emission from an old stellar population is 2-3 times less than that needed to heat the warm ISM (100K). Could the difference be made up from newly formed stars? Shields (1991) performed a survey of H\( \alpha \) emission in X-ray selected, early-type galaxies, finding that the emission from NGC 5866 is extended over the inner \( \sim 4 \) kpc of the galaxy disk and not confined to the nuclear region as seen in the other galaxies in the sample. NGC 5866 was the only case to show this kind distribution for its H\( \alpha \) emission in the sample. A large molecular ISM, strong far infrared (FIR) emission and extensive H\( \alpha \) emission point to ongoing star formation in this galaxy.
Chapter 2

Observations and Data Reduction

The IRAM 30m telescope, located on Pico Veleta, Spain, was used to observe $^{12}$CO emission from NGC 5866. The $J=1-0$ (115 GHz) transition was observed at 9 locations along the optical major axis November, 1998. The observations were made by G. A. Welch and L. J. Sage as part of a volume limited survey of nearby lenticular galaxies. The telescope main beam has a FWHM = 20.9" (1.55 kpc at a distance of 15.3 Mpc) for the $J=1-0$ transition, and the telescope was moved by 11" between observations. Table 2.1 lists the sky positions of each of the pointings. The data were collected using heterodyne receivers which use superconductor-insulator-superconductor mixers and operate in the lower side band mode. The data were obtained in beam-switching mode using a throw of 240" in azimuth at a rate of 1 Hz. Telescope pointing and focus were checked approximately every 2 hours using a bright quasar or the planet Mars. System temperatures were typically 300-400 K for $^{12}$CO $J=1-0$. The raw spectra were collected
using a filterbank spectrometer with a resolution of 1 MHz and a bandwidth of 512 MHz, centred at 745 km s\(^{-1}\). The intensity was measured in terms of main beam temperature.

Data were processed by the author using the CLASS software package for single dish observations. All individual 4 minute scans were summed for each pointing after removing any "bad" channels. The data were binned to a resolution of 10.4 km s\(^{-1}\) using a Hanning smoothing procedure. Each binned spectrum was inspected by eye and a window created to include the emission feature. Linear baseline subtraction then provided values for the integrated intensity (area under the line) and RMS deviation in the baseline. Figures 2.2-2.10 show the pointing data spectra along with the window showing the line width, located under the baseline. The term "line width" is defined here as the velocity range over which there is obvious signal.

**Table 2.1** Coordinates of the 11 \(^{12}\)CO \(J=1-0\) observations. The centre pointing (number 5) is located at \(\alpha(1950) = 15^\text{h}05^\text{m}7^\text{s}.0, \delta(1950) = 55^\circ57'20''\).

<table>
<thead>
<tr>
<th>Pointing Integration Time (minutes)</th>
<th>Offsets (&quot;)</th>
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</table>
Figure 2.1 The IRAM 30m CO J=1-0 observations are superposed on an optical image of NGC 5866. The FOV is $108" \times 85"$. Circles show the telescope FWHM of $21"$ for the J=1-0 transition.
Figure 2.2 This and the following 8 figures show the pointing data and the window used to estimate the line width. The IRAM 30m data for the -35, 27 arcseconds offset (right ascension and declination, respectively) with the baseline subtracted. The line window is also shown under the baseline. The offset in arcseconds is presented in the upper right hand corner.

Figure 2.3 Same as figure 2.2 except the telescope offset is -26, 20 arcseconds
Figure 2.4 Same as figure 2.2 except the telescope offset is -17,14 arcseconds.

Figure 2.5 Same as figure 2.2 except the telescope offset is -9,7 arcseconds.
Figure 2.6 Same as figure 2.2 except the telescope offset is 0,0 arcseconds.

Figure 2.7 Same as figure 2.2 except the telescope offset is 9,-7 arcseconds.
Figure 2.8 Same as figure 2.2 except the telescope offset is $17,-14$ arcseconds.

Figure 2.9 Same as figure 2.2 except the telescope offset is $26,-20$ arcseconds.
Figure 2.10 Same as figure 2.2 except the telescope offset is 35,-27 arcseconds.

The large line widths show that the molecular gas is rotating quickly, with a maximum velocity on the order of 300 km/s. The outer pointings (figures 2.3-2.5 and figures 2.8-2.9) show little evidence for a drop in rotation speed at large radii. The data show that the CO emission lines are complex with peaks and dips seen in the central pointings (figures 2.5-2.8). The centre pointing (figure 2.6) clearly shows more power at lower velocities (below the centre velocity of 745 km/s) compared to higher velocity bins (above 745 km/s). The centre pointing data also suggest a dip in power around the systemic velocity, suggesting less gas in the centre of the galaxy. The 9,-7" pointing (figure 2.7) shows significant signal over almost the same velocity range as the centre pointing. This is interesting since the same effect is not seen when the telescope beam is pointed on the opposite side of the galaxy (figure 2.5). Both the -9,7" and the 17,-14"
pointings (figures 2.5 and 2.8 respectively) show a "saw tooth" shape with a secondary peak around 100 kms$^{-1}$ on either side of 745 kms$^{-1}$ in the respective pointing. The outermost pointings preserve the saw tooth shape in roughly the same velocity bins with progressively weaker signal. This implies that all of the CO in the central region of NGC 5866 has been seen by these observations.
Chapter 3

Results

3.1 The Global Properties of the Molecular ISM

The following gives an overview of the various molecular ISM properties found for NGC 5866 and how the data were used to obtain them. A short discussion on each result is presented, which will be elaborated on in the next chapter.

3.1.1 H$_2$ Mass

In this study the molecular hydrogen content is gleaned from the $^{12}$CO data. CO is thought to be a good tracer of molecular hydrogen since both molecules form in cool regions ($\leq$100 K), and are believed to be well mixed (see Young & Scoville, 1991, for an overview).
The first step in finding the molecular hydrogen mass, $M(\text{H}_2)$, is to integrate the main beam temperature over velocity for all the pointings, as in equation 3.1, to get the integrated CO intensity, $I_{\text{CO}}$.

$$I_{\text{CO}} = \int T_{mb}dV \quad (\text{K km s}^{-1}) \quad (3.1)$$

with $I_{\text{CO}}$ in K km s$^{-1}$, velocity, $V$, in km s$^{-1}$ and main beam temperature in Kelvins, K. The integral is evaluated over the velocity limits of the observed line width (see table 3.1). The uncertainty in $I_{\text{CO}}$ was calculated from the RMS uncertainty in the temperature integrated over the line width for each pointing. The telescope calibration is expected to provide an additional uncertainty of 10-20 % (not reflected in the uncertainties quoted in table 3.1). The CO $J=1$-0 intensities were converted into an $\text{H}_2$ mass, $M(\text{H}_2)$, using several assumptions discussed below.

The relationship between CO and $\text{H}_2$ is described by the CO/$\text{H}_2$ conversion factor, $X_{\text{CO}}$. Since $\text{H}_2$ is not easily detected, another, more accessible molecule must be used as a tracer in order to measure the $\text{H}_2$ indirectly. The $^{12}\text{CO}$ molecule has several rotational transitions which emit radiation at radio wavelengths and are observable through the atmosphere on Earth. $X_{\text{CO}}$ translates the integrated CO intensity into an $\text{H}_2$ column density. Clearly, the accuracy of the conversion factor is essential in order to accurately measure $M(\text{H}_2)$.

The $X_{\text{CO}}$ value of $2.3 \pm 0.3 \times 10^{20}$ molecules/cm$^2$/K km s$^{-1}$, used here, is taken from Strong et al. (1988) who obtain it using CO $J=1$-0 data from all sources in the galactic
plane of the Milky Way with galactic latitude ranging from $-7^\circ$ to $+7^\circ$ and diffuse galactic $\gamma$-ray measurements.

Diffuse $\gamma$-ray emission from the ISM is expected from cosmic ray interaction with Hydrogen atoms. The diffuse $\gamma$-ray intensity, $I_\gamma$, is related to the emissivity, $\varepsilon_\gamma$, and the number of hydrogen atoms, from both atomic and molecular hydrogen, and is expressed as:

$$I_\gamma = \varepsilon_\gamma \{ N(HI) + 2X_{CO} I_{CO} \} \quad (\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}) \quad (3.2)$$

Since $I_{CO}$ is measured directly and $N(HI)$ is obtained independently from 21 cm emission, the $\gamma$-ray data place strict constraints on $X_{CO}$ for the Milky Way (Strong et al., 1988, Bloemen, 1989). The conversion factor most likely depends on the metallicity of the individual galaxy's ISM (e.g. Wilson, 1994, 1995, Taylor et al., 1998), however, there is little evidence to suggest that the metallicity of NGC 5866 and that of the Milky Way is very different. Metallicity is proportional to galactic luminosity (Bothun et al., 1984 use $M_H$ data, Bica & Alloin, 1987 use $M_B$) and the absolute visual magnitudes of NGC 5866 and the Milky Way are quite close: -21.0 and -20.9, respectively (Hamabe et al., 1979, and van den Bergh, 2000, respectively), although the value for the Milky Way is uncertain. Although more work is needed to truly verify the metallicity of NGC 5866, the conversion factor of NGC 5866 is assumed to be the same as that of the Milky Way.

This work assumes a distance of 15.3 Mpc to NGC 5866 (Tully, 1988), in order to be consistent with the data reduction of the rest of the S0 survey members. Estimates for the distance to NGC 5866 vary wildly in the literature (anywhere from 11-25 Mpc) and the
accuracy of many of the results presented here are sensitive to the distance used. For example, small changes in the assumed distance create large differences in the computed H$_2$ masses, since it is proportional to the distance squared (see equation 3.3).

The remaining parameters used to derive $M(H_2)$ are obtained directly; one then has:

$$M(H_2) = 4.267 \times 10^{-19} \theta^2 D^2 \alpha X_{CO} I_{CO} \ (M_\odot)$$  \hspace{2cm} (3.3)$$

where $D$ is the assumed distance in Mpc (15.3 Mpc), $\theta$ is the FWHM of the telescope beam in arcseconds (20.9" for J=1-0), and $\alpha$ is the ratio between the CO/H$_2$ conversion factor in NGC 5866 and the Milky Way ($\alpha=1$). Table 3.1 gives the integrated CO intensities for both transitions and the H$_2$ masses for each pointing. Because the telescope was moved about one half the full width half maximum (FWHM) in the J=1-0 transition between observations, the total H$_2$ mass for NGC 5866 was found by adding every second pointing along the major axis. The mass was calculated a second time using the remaining pointings. Table 3.1 groups the pointings in the way they used to obtain the two estimates for $M(H_2)$. The results were averaged to give

$$M(H_2) = 4.55 \pm 0.43 \times 10^8 \ M_\odot$$  \hspace{2cm} (3.4)$$
Table 3.1 The H$_2$ mass results. The M(H$_2$) values were obtained using equation 3.4. Table 3.2 lists molecular mass values found by other workers for comparison.

<table>
<thead>
<tr>
<th>Offset</th>
<th>Line window</th>
<th>I$_{CO}$ (1-0)</th>
<th>H$_2$ mass</th>
<th>Total H$_2$ mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&quot;]</td>
<td>(km s$^{-1}$)</td>
<td>(K km s$^{-1}$)</td>
<td>($10^7$ M$_o$)</td>
<td>($10^8$ M$_o$)</td>
</tr>
<tr>
<td>1-0</td>
<td>479-606</td>
<td>0.3116 ± 0.80</td>
<td>0.313 ± 0.80</td>
<td></td>
</tr>
<tr>
<td>-17, 14</td>
<td>460-645</td>
<td>5.404 ± 1.18</td>
<td>5.42 ± 1.18</td>
<td></td>
</tr>
<tr>
<td>0, 0</td>
<td>440-1100</td>
<td>22.016 ± 3.41</td>
<td>22.1 ± 3.43</td>
<td>4.32 ± 0.47</td>
</tr>
<tr>
<td>17, -14</td>
<td>715-1050</td>
<td>13.831 ± 2.32</td>
<td>13.9 ± 2.33</td>
<td></td>
</tr>
<tr>
<td>35, -27</td>
<td>866-1100</td>
<td>1.5252 ± 1.58</td>
<td>1.53 ± 1.58</td>
<td></td>
</tr>
<tr>
<td>-26, 20</td>
<td>479-606</td>
<td>2.105 ± 0.83</td>
<td>2.11 ± 0.83</td>
<td></td>
</tr>
<tr>
<td>-9, 7</td>
<td>440-760</td>
<td>12.557 ± 2.09</td>
<td>12.6 ± 2.10</td>
<td>4.78 ± 0.39</td>
</tr>
<tr>
<td>9, -7</td>
<td>475-1140</td>
<td>26.708 ± 2.87</td>
<td>26.8 ± 2.88</td>
<td></td>
</tr>
<tr>
<td>26, -20</td>
<td>815-1045</td>
<td>6.2609 ± 1.31</td>
<td>6.28 ± 1.32</td>
<td></td>
</tr>
</tbody>
</table>

Avg. H$_2$ mass: 4.55 ± 0.43

col. (1) gives the RA and Dec offsets in arcseconds, respectively, col. (2) gives the velocity limits used in equation 3.1, col. (3) is the observed intensity from equation 3.1, col. (4) gives the calculated M(H$_2$) from each pointing and col. (5) gives the total M(H$_2$) value from the two groups of pointings and at the bottom, the average of both totals.

3.1.2 The Molecular to Atomic Hydrogen Gas Ratio

The molecular to atomic gas mass ratio, M$_{H_2}$/M$_{HI}$, in galaxies is often used as a statistical measure against other galaxies of the same type or to compare against other morphological types. This information can be used to explore theories of interaction, gas evolution and environment as all of these factors affect the mass ratio. Previous studies have shown that early-type galaxies often have higher M$_{H_2}$/M$_{HI}$ values than do later types (Casoli et al., 1998). The average molecular to atomic hydrogen mass ratio in S0s is ~0.4
(Casoli et al., 1998) while later types (Sa-Sd) have mass ratio values ~0.3 (Casoli et al., 1998). The samples of Casoli et al. (1998) include members of the Virgo and Coma clusters among others. From a volume limited sample of Sa-Sd galaxies, the median value of $M_{\text{HI}}/M_{\text{HI}} = 0.15$ (Sage, 1993). Many S0 galaxies are found in dense clusters of galaxies and owe their high $M_{\text{HI}}/M_{\text{HI}}$ values to interaction or ram pressure stripping of the HI gas. The $M_{\text{HI}}/M_{\text{HI}}$ ratio in NGC 5866 can be used as a clue as to how its environment might have affected it.

Since no HI has been detected in NGC 5866, the HI mass upper limit, $M_{\text{HI}}$, was calculated from HI flux upper limit of Knapp & Gunn (1982) and equation 3.5. Equation 3.6 (from Haynes & Giovanelli, 1984) assumes that the HI is optically thin and is written as:

$$M_{\text{HI}} = 2.36 \times 10^5 D^2 S \Delta V \quad (\text{M}_\odot)$$

(3.5)

where $S = 6 \times 10^3 \text{ Jy}$ is the observed HI flux in Janskys (Jy), $1 \text{ Jy} = 10^{-26} \text{ Wm}^{-2} \text{Hz}^{-1}$, $D$ is the distance in Mpc and $\Delta V$ in the line width in kms$^{-1}$.

The HI mass was calculated using a line width of 406 kms$^{-1}$ from the stellar and ionized gas rotation curves of Fisher (1997) for NGC 5866 and also a line width of 610 kms$^{-1}$ from the CO data presented here. The results were found to be,

$$M_{\text{HI}} < 1.3 \times 10^8 \text{ M}_\odot \ (\Delta V = 406 \text{ kms}^{-1})$$

(3.6)

$$M_{\text{HI}} < 2.0 \times 10^8 \text{ M}_\odot \ (\Delta V = 610 \text{ kms}^{-1})$$

(3.7)

Table 3.2 lists the various values of $M(\text{H}_2)$ found for NGC 5866 along with the $M_{\text{HI}}/M_{\text{HI}}$ values calculated using the H2 masses listed in column 1 and the HI mass values from
equations 3.6 and 3.7. From table 3.2, $M_{\text{H}_2}/M_{\text{HI}} \geq 3.5$ for NGC 5866 contrasts with the average value of $\sim 0.4$ as found by Casoli et al. (1998) for the average value from a sample of 7 S0 galaxies and 20 S0-a galaxies. Such large $M_{\text{H}_2}/M_{\text{HI}}$ ratios are not unprecedented. However, those are mostly seen in cluster environments where significant interaction is taking place (e.g. NGC 4710, in the Virgo cluster, has a $M_{\text{H}_2}/M_{\text{HI}}$ of $\sim 30$ (Wrobel & Kenney, 1992)). It should be repeated that NGC 5866 is most likely a member of the NGC 5907 loose group of galaxies and that NGC 5907 shows several signs of interaction. The topic of previous interaction in the NGC 5907 group will be explored in chapter 4.

Table 3.2 $\text{H}_2$ masses for NGC 5866, scaled to a distance of 15.3 Mpc, from this work and the literature. The $\text{H}_2$/HI mass ratio lower limits are also given from the 2 HI upper limits shown in equations 3.6 and 3.7.

<table>
<thead>
<tr>
<th>$\text{H}<em>2$ mass $10^8 M</em>\odot$</th>
<th>$M_{\text{H}<em>2}/M</em>{\text{HI}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>$4.55 \pm 0.43$</td>
<td>$\geq 2.3 - 3.5$</td>
</tr>
<tr>
<td>$0.877^a$</td>
<td>$\geq 0.43 - 0.67$</td>
</tr>
<tr>
<td>$6.19^b$</td>
<td>$\geq 3.1 - 4.8$</td>
</tr>
<tr>
<td>$1.31^c$</td>
<td>$\geq 0.66 - 1.0$</td>
</tr>
<tr>
<td>$3.74^d$</td>
<td>$\geq 1.9 - 2.9$</td>
</tr>
</tbody>
</table>

a. Wiklind & Henkel (1989), b. Thronson et al. (1989), c. Taniguchi et al. (1994), d. Young et al. (1995). Col. (1) the $\text{H}_2$ mass from CO measurements scaled to 15.3 Mpc. The varying results reflect different beam sizes and number of pointings used by the various authors. Also, Thronson et al. (1989) use different assumptions about the CO/$\text{H}_2$ conversion factor. Col. (2) the range of molecular gas to atomic gas mass ratios from the largest and smallest derived HI gas masses, $M_{\text{HI}} < 1.3 \times 10^8 M_\odot$ and $< 2.0 \times 10^8 M_\odot$ (flux from Knapp & Gunn (1982) and line widths of 406 kms$^{-1}$ and 610 kms$^{-1}$, respectively).
3.1.3 The Gas to Dust Ratio

The gas to dust ratio is an important quantity since dust is required for the formation of \( \text{H}_2 \) and other molecules. The dust content determines the metallicity of both the ISM and the stars which form from it. The mass of the dust in a galaxy can be inferred from its FIR emission. The dust mass in NGC 5866 was found by using equation 3.8, taken from Thronson et al. (1989) as adapted from Thronson & Telesco (1986) which assumes an opacity of 25 cm\(^2\)g\(^{-1}\) at 100 \( \mu \)m:

\[
M_{\text{dust}} = 5D^2 F_{100}[\exp(144/T_d) - 1] \quad (\text{Mo})
\]  

where the distance, \( D \) is in Mpc, \( F_{100} \) is the IRAS 100 \( \mu \)m flux in Jy (16.1 Jy from the IRAS Faint Source Catalogue) and \( T_d \) is the dust temperature in K (30 K from Thronson et al., 1989). From equation 3.8,

\[
M_{\text{dust}} = 2.3 \times 10^6 \text{Mo}
\]  

which implies \( 200 \leq M_{\text{gas}}/M_{\text{dust}} \leq 300 \), where \( M_{\text{gas}} \) is the mass of the molecular and the atomic Hydrogen. The lower and upper limits are calculated based on the HI mass limits found in section 3.1.2. The gas to dust mass ratio in NGC 5866 is 2-4 times lower than the average value of \( -800 \) which Thronson et al. (1989) give for S0 galaxies with only HI upper limits. That could imply either a deficiency of hydrogen or an overabundance of dust in NGC 5866 compared to similar galaxies. However, it could also be a temperature effect. The gas to dust ratio is found to be \( -800 \) by assuming the temperature of the gas is 38 K instead of 30 K. Thronson et al. caution that the temperature they quote is not an accurate physical temperature but is a measure of the relative abundance of ISM components. The fact that the temperature is so uncertain and that the dust mass equation
is extremely sensitive to the dust temperature used, the gas to dust ratio in NGC 5866 could be considered average within a large uncertainty range.

3.1.4 The Current Star Formation Rate

The central questions of this work are: Where did the gas come from, and where is it going? The second question is addressed in this section. The most obvious mechanism of gas depletion is star formation.

The star formation rate (SFR) of a galaxy can be calculated from its far infrared (FIR) emission. Following Thronson et al. (1989), FIR emission is defined as 40μm-125μm radiation, unless otherwise stated. In normal galaxies FIR radiation is primarily the result of dust grains which have been heated by massive, newly formed stars. That energy is then re-emitted at longer wavelengths. Consequently, the amount of FIR radiation, can be used to measure how many new stars per unit time are forming in the galaxy with an assumed initial mass function, which we will call SFR\(_{\text{FIR}}\). Ionized gas observations in NGC 5866 show that the HII regions are limited to the dust lane so it is a safe assumption that the FIR star formation rate will not be underestimated due to any star formation occurring outside of the dust shroud. The result is an upper limit, however, since stars of all ages actually contribute to heating all forms of dust in the galaxy, producing a global FIR flux. Diffuse dust clouds in galaxies are not associated with any star forming regions, but are heated by the general stellar radiation field and also contribute to the overall FIR luminosity.
All star formation rate calculations depend on the choice of initial mass function (IMF) since the number of stars which can contribute to the heating of the dust is important. The IMF gives the relative number of objects of different mass found in a specific volume of space. In other words, it tells us how many high mass and how many low mass stars are formed from a certain clump of gas. The IMF can be approximated mathematically as:

$$dN = N_0 \xi(M) dM$$  \hspace{1cm} (3.10)

where $N_0$ is a normalizing constant. Equation 3.10 gives the number of stars, $dN$, between mass $M$ and $M+dM$ where $\xi(M)$ is the frequency of creation of a given stellar mass. The Salpeter IMF (Salpeter, 1955) is derived when using a simple power law for the frequency, shown in equation 3.11.

$$\xi(M) \propto M^{-2.35}$$  \hspace{1cm} (3.11)

The Salpeter IMF is only one of many derived from theory and observations. It is perhaps the simplest since it employs a single power law over all masses. Other IMFs use different power laws for different mass ranges (e.g. Miller & Scalo, 1979). Since different initial mass functions predict different amounts of OB stars, the star formation rate is sensitively dependent on the choice of IMF.

The value of SFR$_{\text{FIR}}$ can be found from the far infrared luminosity by making three major assumptions. The first is the average mass to (bolometric) luminosity ratio of a star forming cluster and the second is the time scale on which this cluster produces stars that would heat the surrounding dust. The average mass to luminosity ratio, $\overline{M}/\overline{L}$, is formed using the average stellar mass from an assumed IMF, in this case, the Salpeter
IMF. That is divided by the bolometric luminosity of a star of average mass, found using an assumed luminosity function. Following Thronson & Telesco (1986), values of the luminosity function are taken from table 5 in Telesco & Gatley (1984). The third assumption is that the dust is optically thick to all wavelengths other than FIR, and so its resulting FIR luminosity is essentially the same as the bolometric luminosity of the stars. The star formation rate is therefore written as,

$$SFR_{FIR} = \frac{M}{t_{FIR} \bar{L}} \quad \text{(M}_\odot/\text{yr})$$  (3.12)

where $t_{FIR}$ is the time scale for which young stars heat the dust and $L_{FIR}$ is the FIR luminosity in solar units. The value of $t_{FIR}$ is estimated to be $\sim 2 \times 10^6$ years from observations and theory (Thronson & Telesco, 1986), whereas $\frac{\bar{M}}{\bar{L}}$ equals $1.3 \times 10^{-3}$ $M_\odot/L_\odot$ assuming a Salpeter IMF in the range of 0.1 to 100 $M_\odot$ and the luminosity function of Telesco & Gatley (1984). Combining these quantities gives:

$$SFR_{FIR} = 6.5 \times 10^{-10} L_{FIR} \quad \text{(M}_\odot/\text{yr})$$  (3.13)

The quantity, $L_{FIR}$, is found from:

$$L_{FIR} = 5.6 \times 10^3 D^2 [2.58 F_{60} + F_{100}] \quad \text{(L}_\odot$$  (3.14)

where $F_{100}$ and $F_{60}$ are the IRAS fluxes at 100 and 60 micrometers (16.1 Jy and 4.88 Jy, respectively, from the IRAS Faint Source Catalogue). Equation 3.14 is based on fitting the FIR flux from two wavelengths to a modified black body spectrum incorporating a dust emissivity proportional to $\nu^\alpha$, i.e. $F_\nu \propto \nu B_\nu(T_d)$, typically, $\alpha = 1$. From equation
3.14, $L_{\text{FIR}} = 3.8 \times 10^9 \, L_\odot$ and putting this value into equations 3.13 gives a star formation rate of

$$SFR_{\text{FIR}} = 2.4 \, M_\odot/\text{yr} \quad (3.15)$$

for NGC 5866.

The nature of the time scale, $t_{\text{FIR}}$, is not agreed upon by all authors. Some view the physical interpretation as the time scale on which young OB stars destroy the surrounding medium, while others view it as the time scale on which the starburst takes place (Kennicutt, 1998a). Kennicutt (1998a) uses the mean luminosity and mass of a starburst region ($\sim 1.3 \times 10^8 \, L_\odot$ and $10^6 \, M_\odot$, respectively) given by the models of Leitherer & Heckman (1995) for starburst activity lasting between 10-100 Myr. This time scale is 2 orders of magnitude larger than that of Thronson & Telesco (1986). Writing SFR in the same form and under the same IMF assumptions as equation 3.13, gives:

$$SFR_{\text{FIR}} = 1.73 \times 10^{-10} \, L_{\text{FIR}} \quad (\text{M}_\odot/\text{yr}) \quad (3.16)$$

again with $L_{\text{FIR}}$ in $L_\odot$, however, this time defined as emission at wavelengths between 8-1000 $\mu$m. The far infrared luminosity as defined above was found using equation 3.17,

$$L_{\text{FIR}} = 391484 D^2 C(T_d) [2.58 F_{60} + F_{100}] \quad (L_\odot) \quad (3.17)$$

where $D$ is the distance in Mpc, $F_{100}$ and $F_{60}$ are the IRAS fluxes at 100 and 60 $\mu$m, respectively (same as above) and $C(T_d) = 1.648$ (Helou et al., 1988) is a constant based on the fraction of blackbody radiation with wavelengths between 1-1000 $\mu$m which is seen by the IRAS filters. This wavelength range for FIR is assumed to be consistent with 8-1000 $\mu$m. This gives $L_{\text{FIR}} = 4.3 \times 10^9 \, L_\odot$, a slightly larger value than that derived from equation 3.15. This is a reflection of the larger wavelength range included here.
this definition of $L_{\text{FIR}}$ and equation 3.17, the star formation rate found from the far infrared luminosity is

$$SFR_{\text{FIR}} = 0.75 \, M_\odot/\text{yr} \quad (3.18)$$

Clearly, the choice of IMF, the uncertain nature and value of $t_{\text{FIR}}$, and the assumption of a large optical depth for the dust imply that these equations provide only rough estimates of the true SFR.

3.1.5 The Hα Star Formation Rate

Another measure of the star formation rate in external galaxies is their Hα luminosity, $L_{\text{Hα}}$. Hα emission results from HII regions around hot young stars, and is produced by a recombination of Hydrogen to the first excited level. The electron quickly drops to a lower energy level before the atom is re-ionized by high energy UV photons. The value of $SFR_{\text{Hα}}$ is a lower limit to the actual star formation rate, because dust in the external galaxy and the Milky Way absorbs Hα photons and reduces the flux received on Earth. The Hα luminosity used here has been corrected for foreground extinction. However, the intrinsic extinction from NGC 5866 has not been corrected for, and the contribution to the measured flux due to the [N II] ($\lambda = 6548$ Å and 6583 Å) lines needs to be removed. Shields (1991) assumes an [N II]/Hα ratio of 1.38 for the contribution of [N II] to the total flux. This value is uncertain (5-10%) and is not specific to NGC 5866 (Shields, 1991). Using the Salpeter IMF, the star formation rate via the Hα luminosity, $L_{\text{Hα}}$ is:

$$SFR_{\text{Hα}} = 3.04 \times 10^{-8} L_{\text{Hα}} \quad (\text{M}_\odot/\text{yr}) \quad (3.19)$$
adapted from Kennicutt (1998b) where $L_{\text{H}\alpha}$ is in solar units and the H$\alpha$ star formation rate is in solar masses per year. Using the largest measurement (717.7 pc in diameter at 15.3 Mpc) from Shields (1991), $L_{\text{H}\alpha} = 8.13 \times 10^5 L_\odot$, and scaling to a distance of 15.3 Mpc, the star formation rate is found to be

$$SFR_{\text{H}\alpha} = 0.025 M_\odot/yr$$  \hspace{1cm} (3.20)

Using the upper limit, $L_{\text{H}\alpha} < 1.54 \times 10^6 L_\odot$ from Shields' (1991) largest aperture observation (1.44 kpc in diameter at 15.3 Mpc), the value could be as high as

$$SFR_{\text{H}\alpha} = 0.047 M_\odot/yr$$  \hspace{1cm} (3.21)

These values are on the order of 10 times smaller than $SFR_{\text{FIR}}$ from equation 3.16. This is a reflection of the fact that the $SFR_{\text{H}\alpha}$ of equation 3.19 makes no correction for intrinsic extinction and assumes that all UV photons are absorbed by the HII gas. Also, the apertures do not see as much emission due to their small sizes. Given the large uncertainties, it is not surprising that these values appear to be so different. Indeed, many workers have found higher star formation rates from FIR data than from H$\alpha$ (e.g. Hopkins et al., 2001). The FIR luminosity has an unknown fraction of its flux not related to star formation while the observed H$\alpha$ flux is most certainly lower than the actual flux due to reasons mentioned above.

### 3.1.6 The Gas Consumption Timescale

The star formation efficiency (SFE) is another useful quantity to answer the question of where is the gas going. The SFE is a measure of how much gas is being used up forming stars relative to the amount of gas available. Following Thronson & Telesco (1986) the
SFE can be expressed in terms of what fraction of the molecular gas is being turned into stars in a given year.

\[
SFE = \frac{SFR}{M(H_2)} \text{ (yr}^{-1}\text{)}
\]  

(3.22)

When using the SFR\text{FIR} of equation 3.15, the star formation efficiency is

\[
SFE = 5.3 \times 10^{-9} \text{ yr}^{-1}
\]

(3.23)

Thus, by taking the inverse of this result, the present star formation rate can be maintained for \(\sim 2 \times 10^8\) years. This is only a small fraction of the age of the universe so, assuming a constant star formation rate, the gas must be replenished from some source in order to be seen today. Using the Kennicutt (1998a) SFR\text{FIR} from equation 3.18, the star formation efficiency becomes,

\[
SFE = 1.44 \times 10^{-9} \text{ yr}^{-1}
\]

(3.24)

This rate can be maintained for approximately \(7 \times 10^8\) years, still a short length of time on cosmological scales. The lowest star formation rate is given by the H\alpha data and reveals a star formation efficiency of

\[
SFE = 5.5 \times 10^{-11} \text{ yr}^{-1}
\]

(3.25)

showing that star formation can continue at the present rate for \(\sim 18\) Gyr. Using the H\alpha flux upper limit formation rate gives a star formation efficiency of

\[
SFE = 1.0 \times 10^{-10} \text{ yr}^{-1}
\]

(3.26)

which means star formation can continue on the order of 10 Gyr. However, these gas consumption time scales are lower limits since no replenishment of the ISM has been considered.
The mass return rate, as calculated from Faber & Gallagher (1976) for NGC 5866 is 0.10 \( \text{M}_\odot / \text{yr} \). This is \( \sim 25 \) times less than the largest star formation rate from the far infrared data. Assuming the higher star formation rate, it would seem that NGC 5866 will consume its gas supply on the order of \( 10^8 \) yrs while it would take \( \sim 6 \) Gyr to replenish \( 4.55 \pm 0.43 \times 10^8 \text{ M}_\odot \) of \( \text{H}_2 \) from simple mass return arguments. This suggests that the star formation rate might oscillate on time scales on the order of several billion years. A common measure of how the current star formation rate compares to the average past SFR is the ratio, \( L_{\text{FIR}} / L_B \) (e.g. Wiklind & Henkel, 1990). This assumes that the blue luminosity, \( L_B \), is proportional to the star formation rate averaged over the last \( 10^9 \) years i.e. that \( L_B \) is associated with lower mass stars than those responsible for most of the far infrared emission (Thronson & Telesco, 1986, references therein). For NGC 5866,

\[
L_{\text{FIR}} / L_B = 0.22
\]  

(3.27)

using \( L_B \) from Tully (1988). The \( L_{\text{FIR}} / L_B \) value found here is roughly half the average value of \( \sim 0.40 \) found for normal spiral galaxies and \( \sim 0.35 \) found for S0s (de Jong et al., 1984). The low value of \( L_{\text{FIR}} / L_B \) implies that the star formation rate of NGC 5866 was higher in the past if we assume that the SFR has been roughly constant over time in normal spirals.

If either of the H\( \alpha \) star formation rates is correct then NGC 5866 is roughly in mass balance since the present star formation rate can be maintained over a Hubble time. Given the large uncertainties in the SFR calculations, the upper limit star formation rate from the H\( \alpha \) data of 0.047 \( \text{M}_\odot / \text{yr} \) will be used. This is a compromise between the upper limits set by the far infrared data, which is believed to be the least accurate of the two
measures, and the lowest value from the Hα data. A simple calculation shows that the total cool ISM mass should be $5.3 \times 10^8 \, M_\odot$. This is found by subtracting the total mass consumed by star formation in $10 \, \text{Gyr}$ from the total mass returned in the same time. The result is on the order of $6.4 \times 10^8 \, M_\odot$ found by scaling up the molecular hydrogen mass to include Helium.

### 3.2 Morphology and Kinematics of the Molecular Gas

A computer model was used to help answer questions regarding the morphology and kinematics of the molecular gas in NGC 5866. COSPEC is a FORTRAN program used to simulate observed $^{12}\text{CO}$ line spectra. COSPEC models an infinitely thin rotating disk or ring of optically thick $^{12}\text{CO}$. When discussing the models in general, the term "disk" is used since a ring is simply a special case of a disk in COSPEC. The disk can be of any angular size and rings of any angular radius. The model can be viewed at any inclination on the sky and at any angle to the major axis. The CO can be distributed in a choice of several different intensity profiles: constant intensity disk or ring, Gaussian disk or ring, exponential disk or truncated Gaussian ring. The disk models have their maximum intensity values at the centre. The model rotates as prescribed by a user defined rotation curve. The model allows the user to synthesize the complex structure in an observed spectrum by introducing co-moving regions of either lower or higher intensity into the chosen intensity profile. These "clouds" are transparent to one another so that no shadowing takes place. The code does not constrain the absolute physical cloud properties but does allow one to gauge roughly where they could be found in physical space and also suggests what their size and relative brightness might be. The program
also allows for the inclusion of a velocity dispersion component to any model. The velocity dispersion is incorporated using a Monte-Carlo simulation of an assumed Gaussian velocity distribution (Box-Mueller algorithm, Bevington & Robinson, 1992). The simulated spectra and the observations are plotted together for visual inspection and a "goodness of fit" value is calculated by summing the squares of the intensity differences in each velocity bin over the observed line.

For this project, the convolving beam is an approximation of the IRAM 30m power pattern for the J=1-0 CO transition (Greve et al., 1998). The central pointing in the model (3" offset in this case) is normalized to the 0,0 pointing data. The model offset is 3" as opposed to zero, when simulating the 0,0 pointing, in order to best reproduce the centre pointing without complicating the model. 3" is considered to be within the uncertainty of the telescope pointing. The scale factor needed to equalize the model and the integrated intensities at this pointing is used for all other pointings. The source code is presented in appendix A and further details of the parameters and how the code was used in this work can be found in appendix B. In this work, the term "best fit model" refers to the model which best reproduced the observed spectra based on the goodness of fit parameter.

3.2.1 The Distribution of Molecular Gas in NGC 5866

The gas was best modelled by a Gaussian ring distribution with an outer radius of 30" seen edge-on. This is about the observed length of the optical dust lane in NGC 5866. The intensity peaked at a radius of 15", with a FWHM of 15". Several asymmetries or
"hot" and "cold" spots (called clouds and holes, respectively henceforth) were included to better fit the observed spectra. A unique distribution of asymmetries cannot be found based on the limited nature of the data, but clearly there are regions of greater intensity on the redshifted side relative to the blueshifted side. Table 3.3 lists the asymmetry parameters. There are several large regions of depressed intensity (~3-6" in diameter) located mostly at the same radius as the centre of the Gaussian ring. The necessity of these holes to improve the model argues for a broken ring structure for the molecular gas distribution. This is a common form of gas distribution in galaxies (Pogge & Eskridge, 1987). Most notably, the lenticular galaxy, NGC 404, has its molecular gas distributed in a ring with several pieces missing (Wiklind & Henkel, 1990). The areas of higher intensity are possibly giant molecular clouds warmed by the light from recently formed stars. The brighter clouds introduced in the model are on the order of 200 pc in size and make up only ~4% of the intensity output. This corresponds to a cloud mass of ~10^6 M☉. These clouds are comparable in size and mass to the larger the giant molecular clouds in the Milky Way (Dame et al., 2001). Figure 3.1 shows a diagram of how the holes and clouds are distributed in the model disk. Table 3.3 lists the parameters used in the best fit model.

The models were judged on the basis of how well they could synthesize the 4 central pointings (offsets seen in figures 3.5-3.8). The 4 central pointings show the strongest signal and have unique spectral shapes. The shapes of the outer pointings basically preserve the saw tooth pattern and so no new complications to the model are needed to synthesize these pointings. Figures 3.2 through 3.10 show the simulated spectra of the
best fit model, plotted with the data for comparison. The best model was found by first finding a rotation curve which could match the observed line width qualitatively. To begin, published stellar and ionized gas rotation curves for NGC 5866 (Fisher, 1997) were attempted, but failed to provide a reasonable fit. Section 3.2.2 discusses the Fisher (1997) data further. With the chosen rotation curve, several different intensity profiles where modelled starting with a simple constant intensity disk and on through the various distributions mentioned above (see appendix C for details and results of these experiments). A Gaussian ring (described above) was chosen as best based on the goodness of fit parameter and several asymmetries were included in order to match the spectra (table 3.3). Details on the parameter choosing process can be found in appendices B and C. For example, the Gaussian ring model without asymmetries is compared to the best fitting Gaussian disk (FWHM = 45") model in figures 3.11-3.14. The goodness of fit parameter is slightly lower at 0.224 for the Gaussian ring as opposed to that of the Gaussian disk, 0.238. The main benefit of a ring model over a disk is clear in figure 3.12. The goodness parameter is ~30% lower in the ring model. The low observed power around the systemic velocity of 745 kms$^{-1}$ favours distributions with less power near the centre. The saw tooth pointings (figures 3.11, 3.14) are basically the same for both models. This is not surprising since the outer edge of a ring and a disk look basically the same. Also, for comparison, figures 3.15-3.18 show how the asymmetries improve the plain Gaussian ring model. The average goodness of fit parameter drops to 0.200 from 0.224, an improvement of ~10%. The asymmetries are most obvious in figure 3.16. The model still contains too much power in the centre but matches the shape of the spectra more closely. The plain Gaussian ring model provides too much power at the peak of the
saw tooth pointings, however the addition of several "holes" was effective at lowering the peaks (figures 3.15, 3.18). The asymmetries also helped to flatten out the peak seen in figure 3.17, and although, still too powerful, the best fit model is a closer match the shape of the spectrum.

Figure 3.1 A schematic of the best fit model viewed face on (parameters used in this model are found in table 3.3). The azimuth of the cardinal locations is shown on the diagram. The arrows indicate the direction of rotation. The offsets for the convolving beam can be surmised from the distances listed on the bottom. The green circles locate the FWHM of the Gaussian ring. Blue circles represent the holes added to the model and the red circles represent the clouds incorporated into the model. The line of sight is perpendicular to the plane of the page looking from the bottom to the top.
Table 3.3 This table lists all of the parameters necessary to generate the COSPEC model which best matched the data. The results of this model are presented in the box at the bottom of the table. Figure 3.1 illustrates the geometrical quantities.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systemic velocity (km(s^{-1}))</td>
<td>745</td>
</tr>
<tr>
<td>Max. rotational velocity (km(s^{-1}))</td>
<td>305</td>
</tr>
<tr>
<td>Transition</td>
<td>J=1-0</td>
</tr>
<tr>
<td>Disk size (&quot;)</td>
<td>60</td>
</tr>
<tr>
<td>Kink vel. in rot. curve (km(s^{-1}))</td>
<td>200</td>
</tr>
<tr>
<td>Kink radius in rot. curve (&quot;)</td>
<td>10</td>
</tr>
<tr>
<td>Tip (degrees)</td>
<td>90</td>
</tr>
<tr>
<td>Pointing</td>
<td>()</td>
</tr>
<tr>
<td>Offset (code)</td>
<td>()</td>
</tr>
<tr>
<td>CLASS RMS</td>
<td>(K)</td>
</tr>
<tr>
<td>Cloud #</td>
<td></td>
</tr>
<tr>
<td>Rad. position (frac. of disk)</td>
<td></td>
</tr>
<tr>
<td>Azimuth (degrees)</td>
<td></td>
</tr>
<tr>
<td>Intensity (scalar)</td>
<td></td>
</tr>
<tr>
<td>Size (&quot;)</td>
<td></td>
</tr>
<tr>
<td>Size (cu)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
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</tr>
<tr>
<td>5</td>
<td>0.28</td>
</tr>
<tr>
<td>6</td>
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</tr>
<tr>
<td>8</td>
<td>0.9</td>
</tr>
<tr>
<td>9</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>Mod. type</td>
<td></td>
</tr>
<tr>
<td>Norm. co</td>
<td></td>
</tr>
<tr>
<td>Ring Rad. (&quot;)</td>
<td></td>
</tr>
<tr>
<td>FWHM frac. Disk</td>
<td>0.25</td>
</tr>
<tr>
<td>Pointing (&quot;)</td>
<td></td>
</tr>
<tr>
<td>Results</td>
<td></td>
</tr>
<tr>
<td>Goodness</td>
<td>0.168</td>
</tr>
<tr>
<td>Avg. good</td>
<td>0.200</td>
</tr>
<tr>
<td>Gauss ring</td>
<td>2.54952E-04</td>
</tr>
</tbody>
</table>

This table is presented in order to give the reader the full set of parameters needed to generate the best fit model. The units used above match those referred to in the code unless otherwise stated here. The upper left portion of the table lists the basic parameters of the rotation curve and disk. The term "size" refers to diameter. The "kink" velocity and radius refer to the location on the rotation curve where there is a change in regime. Essentially, the rotation curve rises to 200 km/s at 10" and then continue to rise to the maximum rotational velocity (305 km/s) at the edge of the disk (30"). The term "tip" is the program name for the inclination of the disk (see appendix B for a detailed description of the COSPEC parameters). Since NGC 5866 is an edge on galaxy, the model uses an inclination of 90° to best simulate the data. Directly below the tip parameter is a list of the asymmetry parameters. These include the radial position, azimuth, intensity and size. Size is listed twice, once in " and once in computer units, cu. To run the code, the clouds sizes are input in cu. Figure 3.1 shows the asymmetries pictorially. Below the cloud parameters are the specific values of the Gaussian ring parameters. The upper right hand corner of the table lists how the telescope offsets and the COSPEC offsets match up along with the RMS uncertainty in the intensities as found by the CLASS data reduction software. These values are needed for computing the goodness of fit.
Looking at the best fit model again, the 9",-7" pointing (figure 3.7) is clearly the worst fit of the 4 central pointings. The excess power between 440-750 kms$^{-1}$ could not be simulated with this simple model. It might represent molecular gas with distinct kinematics or an error in pointing. The latter seems unlikely since the 0,0 pointing data (figure 3.6) also show excessive power on the redshifted side, arguing that this is a real effect. Attempts to model the 9,-7 pointing by choosing offsets closer to the centre only slightly improved the fit ($\sim6\%$) at an offset of $-6"$ (as opposed to $-8"$). Offsets closer to 0" gave progressively worse fits overall but did fit the blueshifted side better between 475 and 745 kms$^{-1}$. Another strange feature of the 9,-7 pointing is the extra power found in the 945-1140 kms$^{-1}$ bins. This looks like it could be an effect of velocity dispersion since it seems to be smoothing out the peak. Models with an adopted velocity dispersion matched this pointing slightly better in the 945-1140 kms$^{-1}$ velocity bins since velocity dispersion necessarily adds power above the highest velocity given by the rotation curve (and also below the lowest velocity), figure 3.21 shows this effect. The other major difficulty with the model is the excess power seen at the peaks of both of the "saw tooth" spectra seen in figures 3.5 and 3.8. This could be reconciled by adding more holes to the model or requiring that the intensity drop off faster at larger radii. Indeed, Gaussian ring models with smaller FWHM do fit the saw tooth spectra better, but are worse on the whole. The simulated spectrum for the $-26",20"$ offset (figure 3.3) has power too blueshifted compared to the data by about 50 kms$^{-1}$. This might means that the rotation curve drops back to a slightly lower velocity near the observed radius. However, the corresponding redshifted signal (figure 3.9) does not imply a drop in the rotation curve. This is might be due to the slight systematic shift in offsets between to the model and the
pointings (3")", which was necessary to best model the 4 central pointings. Figure 3.10 might be consistent with slightly reduced rotational speeds, but the signal is too faint to provide compelling evidence.

![Graph showing velocity vs. temperature](image)

**Figure 3.2** This and the following eight figures show how the best fitting model compares to the observations. The darker line is the Gaussian ring model with asymmetries (ring radius = 15", FWHM = 15") plotted with the data (thin, noisy line). The model offset is 47". The parameters used to generate this and the other spectra in figures 3.2 through 3.10 are found in table 3.3. The telescope pointing offset in arcseconds and "the goodness of fit" of the model to the data is recorded in the upper right hand corner of the chart box.
Figure 3.3 Same as Figure 3.2 except the model offset is 36".

Figure 3.4 Same as Figure 3.2 except the model offset is 25".
Figure 3.5 Same as Figure 3.2 except the model offset is 14".

Figure 3.6 Same as Figure 3.2 except the model offset is 3".
**Figure 3.7** Same as Figure 3.2 except the model offset is \(-8''\).

**Figure 3.8** Same as Figure 3.2 except the model offset is \(-19''\).
Figure 3.9  Same as Figure 3.2 except the model offset is -30".

Figure 3.10  Same as Figure 3.2 except the model offset is -41".
This and the following three figures show how a Gaussian ring model and a Gaussian disk model differ. The red line is the Gaussian ring model with no asymmetries (ring radius = 15" and FWHM = 15"), the green line is the Gaussian disk model which best matched the data (FWHM = 45") and the noisy black line is the data. The model offsets are 14". The telescope pointing offset in arcseconds and the "goodness of fit" for each model is recorded in the top right hand corner.

Same as Figure 3.11 except the model offsets are 3".
Figure 3.13 Same as Figure 3.11 except the model offsets are $-8^\circ$.

Figure 3.14 Same as Figure 3.11 except the model offsets are $-19^\circ$. 
Figure 3.15 This and the following three figures illustrate how the addition of asymmetries to the plain Gaussian ring improve the model. The red and black lines are the same as in figures 3.11-3.14. The green line is the Gaussian ring model (ring radius = 15", FWHM = 15") with the asymmetries (as in Figures 3.2-3.10). The telescope pointing offset and the "goodness of fit" for each model is located in the upper right hand corner. The model offsets are 14".

Figure 3.16 Same as Figure 3.15 except model offsets are 3".
Figure 3.17 Same as Figure 3.15 except the model offsets are $-8''$.

Figure 3.18 Same as Figure 3.15 except the model offsets are $-19''$. 
In an effort to further improve the model fit to the data, the edge-on, Gaussian ring was tilted from the line of beam pointings, thereby making the power pattern further away from the emitting ring for the outer pointings. Using different asymmetry distributions in the Gaussian ring, the tilted models could indeed improve the fit to the data slightly. The goodness parameter declined by only a few percent over the best fit model reported in table 3.3. If the molecular gas in NGC 5866 has been accreted from an external source, it is possible that it has not yet settled into the plane of the galaxy. Another possibility is that the molecular ring is not tilted but warped at larger radii. The tilted ring model would produce spectra that look the same as a warped disk or ring at large radii. Both would move the source further away from the power pattern beam and produce spectra with less power than expected. Figure 3.4 clearly shows the best fit model produces too much power but reproduces the same shape. A tilt or warp in the gas distribution would correct this. The tilted models were not adopted because they suggest that the molecular gas is not closely traced by the optical dust lane, a seemingly improbable result based on the well known, close association between molecular gas and dust in spiral galaxies.

### 3.2.2 The Kinematics

One of the most curious results is how the molecular gas appears to be rotating. The broad lines (~610 km s⁻¹) in the spectra and the constant position of the saw tooth shape in velocity space across the galaxy, shown in chapter 2, clearly reveal a large rotational velocity. Fisher (1997) published rotation curves of the stars and [O III] (5007 Å) based on line-of-sight velocity distribution data for 18 S0 galaxies, including NGC 5866. The data reveal that the stellar rotation curve rises linearly up to 200 km s⁻¹ at a radius of about
30". The ionized gas, presumably the result of HII regions, rotates in two regimes, rising quickly to \(~68 \text{ kms}^{-1}\) at 2.5" and then again, showing a linear rise up to 200 kms\(^{-1}\) at 30". The curve appears to level out but there is no [O III] data past 30". Attempts to model the CO spectra with the observed stellar and [OIII] rotation curves from Fisher (1997) failed to reproduce the observations due to the fact that both rotation curves reach maximum values near 200 kms\(^{-1}\). Figure 3.19 shows the stellar rotation curve from Fisher (1997) and the approximation to it used by COSPEC. Figure 3.20 shows Fisher's data together with the approximation used by the program. Figure 3.21 shows both the stellar and [OIII] data of Fisher along with a rotation curve needed to reproduce the CO observations. The molecular gas is rotating very rapidly. Within a radius of 10" the required rotation curve rises to 200 kms\(^{-1}\); a stark contrast to the rotation of the stars and ionized gas found by Fisher (1997). At this radius the stars and the ionized gas are rotating at around 75 kms\(^{-1}\). The molecular gas rotation curve continues to rise out to 30" where it peaks at 305 kms\(^{-1}\). There might be evidence of the gas slowing down further out as the large offset pointings still show the "saw tooth" pattern at slightly shifted velocity bins. Figures 3.3-3.4 and 3.9-3.10 are examples of this.
Figure 3.19 The Fisher (1997) stellar rotation curve data (yellow) and the approximation to it used by COSPEC (blue).

Figure 3.20 The Fisher (1997) [O III] rotation curve data (blue) and the approximation to it used by COSPEC (pink).
Figure 3.21 The Fisher (1997) stellar (yellow) and [O III] (blue) rotation curve and the best fit rotation curve used by COSPEC (red).

The large rotation speed implies that the molecular gas is decoupled from both the stars and the ionized gas. The bend in the rotation curve reveals that the gas rotates in two separate regimes.

The issue of why the CO line width is on the order of 200 kms$^{-1}$ wider than that predicted by the [O III] rotation curve was addressed by running models which used the stellar and [O III] rotation curves found in Fisher (1997) along with a radially declining velocity dispersion component. These models test whether the large line width is due both rotation and velocity dispersion. In these models, the velocity dispersion is interpreted to be large scale motions of the CO and not a result of Doppler shifted signal from individual molecules. With velocity dispersion, the maximum rotation speed can be lower than when rotation is assumed to be the only factor which determines the line
width. Fisher (1997) finds that the [O III] velocity dispersion peaks in the centre at \( \sim 120 \) km\( s^{-1} \) and drops as the radius increases; this was assumed to be appropriate for the CO. The best fitting Gaussian ring intensity distribution (ring radius of 15" and a FWHM of 15") was used along with the stellar and [O III] rotation curves, both with and without velocity dispersion for comparison. The results are shown in figures 3.22-3.29. Figures 3.22-3.25 show the stellar rotation curve with and without velocity dispersion. Including a velocity dispersion improves the goodness of fit parameter for this model by \( \sim 20\% \), dropping the average value from 1.34 to 1.09. Figures 3.26-3.29 show the same thing only using the [O III] rotation curve. The [O III] rotation curve improves the fit over the stellar rotation curve regardless of velocity dispersion due to the slightly higher rotation speed and the faster rise out to \( \sim 2.5" \). The [O III] rotation curve still provides a poor fit, however. Again, velocity dispersion improves the fit, this time by \( \sim 30\% \) with a goodness of fit parameter going from 1.17 to 0.897. Clearly, including a velocity dispersion does improve the fits, but does not reproduce the line width seen in the data. This suggests that the molecular gas is truly rotating more rapidly than the stars and the ionized gas.
Figure 3.22 This and the following three figures show how the a Gaussian ring distribution using the stellar rotation curve, with and without velocity dispersion match the data. The green line is the Gaussian ring model (ring radius = 15", FWHM = 15") using the stellar rotation curve for NGC 5866 found in Fisher (1997), the red line is the same model with a velocity dispersion component. The telescope pointing offset and the goodness of fit for each model is recorded in the upper right hand corner. The model offsets are 14".

Figure 3.23 Same as Figure 3.22 except the model offsets are 3".
Figure 3.24 Same as figure 3.22 except the model offsets are –8".

Figure 3.25 Same as Figure 3.22 except the model offsets are –19".
Figure 3.26 This and the following three figures show how the a Gaussian ring distribution using the [O III] rotation curve, with and without velocity dispersion match the data. The green line is the Gaussian ring model (ring radius = 15", FWHM = 15") using the [O III] rotation curve for NGC 5866 found in Fisher (1997), the red line is the same model with a velocity dispersion component. The telescope pointing offset and the goodness of fit for each model is recorded in the upper right hand corner. The model offsets are 14".

Figure 3.27 Same as Figure 3.26 except the model offset is 3".
Figure 3.28 Same as Figure 3.26 except the model offsets are $-8^\circ$.

Figure 3.29 Same as Figure 3.26 except the model offsets are $-19^\circ$. 
A velocity dispersion component was also added to the best fit model. Figures 3.30-3.33 show how the Gaussian ring distribution with asymmetries and the same model with velocity dispersion compare to the data. Since the best fitting model does not include a velocity dispersion, it is not surprising that it does not improve the fit (average goodness with velocity dispersion of 0.26 as opposed to 0.20 for the best fit without velocity dispersion). That is, the best fitting model was found by adding asymmetries to correct for deviations from a plain Gaussian ring and a rotation curve which allowed for a 610 kms\(^{-1}\) wide line. Velocity dispersion only smears these out the asymmetries and overextends the line at the saw tooth pointings. The only exception is \(~10\%\) improvement the 9,-7 pointing (figure 3.32) which was discussed in section 3.2.1.

![Figure 3.30](image)

**Figure 3.30** This and the following 3 figures illustrate the difference in the models when velocity dispersion is added to the best fit model. The green and black lines are the same are Figures 3.15-3.18. The purple line is the Gaussian ring model (ring radius = 15", FWHM = 15") with asymmetries and a velocity dispersion component. The telescope pointing in arcseconds and the goodness of fit for the two models is recorded in the upper right hand corner. The model offsets are 14".
Figure 3.31 Same as Figure 3.30 except the model offsets are 3\".

Figure 3.32 Same as Figure 3.30 except the model offsets are -8\".
Despite the fact that velocity dispersion does slightly help reconcile the 9,-7 pointing model with the data, the assumption that the CO everywhere has the same velocity dispersion as the ionized gas is probably not a good one. The steep drop in intensity of the saw tooth line shapes seen in figures 3.5 and 3.8, for example, argue against a large velocity dispersion. This is clear when comparing the models with and without velocity dispersion (figures 3.30 and 3.33, for example). The power tapers off more slowly when velocity dispersion is included, showing slight power between 1040 and 1110 kms$^{-1}$. 

Figure 3.33 Same as Figure 3.30 except the model offsets are −19".
Chapter 4

Discussion

4.1 Comparison to Other Early-Type Galaxies

4.1.1 The $M_{\text{H}_2}/M_{\text{HI}}$ Ratio

Henkel & Wiklind (1997) list 12 S0 galaxies with both H$_2$ and HI detections in their review of the cool ISM in early-type galaxies, within 25 Mpc, excluding Virgo cluster members. On average, $M_{\text{H}_2}/M_{\text{HI}} = 0.44$ for this sub-sample of their work, whereas $M_{\text{H}_2}/M_{\text{HI}} \geq 3.5$ for NGC 5866. The volume limited sub-sample of 7 S0 galaxies, again within 25 Mpc, again excluding Virgo cluster members, from Thronson et al. (1989) shows an average $M_{\text{H}_2}/M_{\text{HI}}$ of $\sim 1.7$. The volume-limited survey of Welch & Sage find an average $M_{\text{H}_2}/M_{\text{HI}} = 0.23$ for 9 S0 with positive HI detections in their sample (Welch, 2001). For the 10 S0s with only HI upper limits, a median value of 0.85 is found, however, they list a $M_{\text{H}_2}/M_{\text{HI}}$ lower limit for NGC 5866 of 0.87 (Welch, 2001). This value scales to 2.61 when taking into account that the upper limits on the HI mass are at the 3 sigma level. Since no solid conclusions can be made when the amount of HI is
unknown it is difficult to assess the true nature of the $M_{\text{H}_2}/M_{\text{H}i}$ is NGC 5866. However, based on the comparison to galaxies with positive HI detections, it would seem that $M_{\text{H}_2}/M_{\text{H}i}$ is somewhat high in NGC 5866. The reader should be reminded that there have been no positive detections of atomic Hydrogen in NGC 5866 and so the ratio could indeed be much higher than 3.5.

The H$_2$ surface density is one measure which can test whether the molecular to atomic Hydrogen mass ratio is a result of an overabundance of H$_2$ or a lack of HI, when compared to similar galaxies. Following Sage & Wrobel (1989) the surface density, $\Sigma_{H_2}$, was calculated using equation 4.1:

$$\Sigma_{H_2} = \frac{M_{H_2}}{(\pi D_{25}^2 / 4) (M_\odot/pc^2)}$$

(4.1)

In this equation $D_{25}$ is defined as the diameter at 25$^{th}$ magnitude/arcsecond$^2$ isophote in blue light and is taken from the Tully *Nearby Galaxies Catalogue* (see table 4.1). One then finds $\Sigma_{H_2} \approx 0.6 M_\odot/pc^2$, which is essentially the same as the median value found by Sage & Wrobel (1989) for their sample of S0s. This might imply that the large value of the $M_{\text{H}_2}/M_{\text{H}i}$ ratio is due to a lack of HI in NGC 5866 and not an excess of H$_2$, however, many of the S0s in Sage & Wrobel's (1989) sample also have no detected HI. Regardless, it would seem that NGC 5866 does have a normal H$_2$ abundance. The presence of H$_2$ and the lack of HI is not unique to NGC 5866. Knapp (1998) reports that 47% of S0s have H$_2$ (43 galaxies surveyed) while only 20% have HI detections (103 galaxies surveyed). These percentages are most likely biased by Virgo cluster members, however, the point that a solely molecular cool ISM is not unique remains. Elmegreen
(1993) showed that the molecular and atomic ISM is sensitive to changes in pressure. A slight increase in pressure is capable of converting entire HI regions into H₂. Self-shielding from ambient radiation inside gas clouds increases sensitively with pressure. A pressure change can be caused by a close passage of a companion, for example. This might not cause collapse of a gas cloud but only a phase change. Since the H₂ surface density in NGC 5866 is normal for an S0 galaxy, and the molecular to atomic hydrogen mass ratio is higher than average, this suggests that the HI is absent and not simply converted into molecular gas.

4.1.2 The Star Formation Rate

The interstellar medium seems normal in its star formation rate based on a sample of similar galaxies. Thronson et al. (1989) calculated SFR\textsubscript{FIR} for 5 IRAS selected, X-ray emitting S0 galaxies, including NGC 5866, finding a SFR\textsubscript{FIR} = 1.3 M\textsubscript{☉}/yr for NGC 5866, based on a distance of 11 Mpc (scaling to 15.3 Mpc gives 2.52 M\textsubscript{☉}/yr, virtually identical to the SFR presented in equation 3.16), while the average for the sample is SFR\textsubscript{FIR} = 1.25 M\textsubscript{☉}/yr. Caldwell, Kennicutt & Schomer (1994) find an average SFR\textsubscript{Hα} = 4 \times 10^{-3} M\textsubscript{☉}/yr for a sample of 8 S0 galaxies within 40 Mpc (H\textsubscript{₀} =75 kms\textsuperscript{-1}/Mpc), around 10 times lower than SFR\textsubscript{Hα} = 0.047 M\textsubscript{☉}/yr found here for NGC 5866. Defining an average star formation rate is difficult due to the varied values obtained by the different methods of calculating SFR and the differing assumptions that go into each model. The results shown in the previous chapter seem to be average or slightly above for an S0 galaxy, based on the Thronson et al. (1989) results.
4.1.3 The CO Distribution

The kinematic model of NGC 5866 reveals that the molecular gas is most likely in a Gaussian ring distribution with large holes in the ring and several "hot" spots, mostly on one side. Molecular rings in spirals are fairly common (Pogge & Eskridge, 1993, Regan et al., 2001). The Milky Way contains an inner molecular ring of radius ~190 pc (Oort, 1977, and references therein) and the CO line emission from this ring has approximately a Gaussian radial profile (Sumin, Fridman & Khaud, 1991). The Milky Way also has a ring of molecular clouds which span a radius range of 4 to 8 kpc and is peaked at 5.5 kpc < R < 6.5 kpc (Sanders, Scoville & Solomon, 1985). Pogge & Eskridge (1993) find 10 out of 14 S0 galaxies with HII disks (10 of 32 in the full S0 sample) have ring-like distributions of HII regions, implying that the molecular gas from which the newly formed stars which ionize the gas is also distributed in the same fashion. The ring radii vary between 0.24 kpc to 14.9 kpc having a median value of 2.32 kpc which is similar to the 1.1 kpc molecular ring assumed for NGC 5866 from the models. Lesch et al. (1990) propose that all spiral galaxies with rotation curves which change from rigid body to differential rotation at some transition radius, r_t, should have a gas ring. The physical mechanism is that angular momentum is carried out radially in the differential rotation regime causing gas to fall inward towards r_t due to viscosity. The NGC 5866 model rotation curve, however, does not contain a differentially rotating regime, nor is one suggested by Fisher's (1997) data until past a radius of 30". Gas rings might also arise through galaxy harassment (Icke, 1985) or a merger (Sofue, 1994). Therefore, it is not surprising to find a ring like distribution of molecular gas in NGC 5866 since rings can be produced by both internal and external mechanisms.
The simple kinematic model provides reasonable fits for all pointings except the 9,-7 offset (figure 3.7). The telescope was pointed toward the redshifted side of the galaxy but there is clearly excess signal compared to the model below the systemic velocity (745 kms\(^{-1}\)). This extra blueshifted intensity cannot be accounted for by a simple Gaussian ring or any of the attempted intensity profiles (see appendices B & C). The signal in the lower velocity bins could be the result of a pointing error, which, however, seems unlikely since it would imply a pointing error of ~5" for the one pointing only and various models with offsets between 0" and -8" failed to reproduce the spectrum width. It could also be that at the 9,-7 offset the telescope views gas whose kinematics differs from that assumed in the simple model. This could be a large amount of gas perturbed by a supernova event. Another possibility is a second, smaller disk or ring viewed by the 9,-7 pointing. The extra signal in the data compared to the model is on the redshifted side (~900-1050 kms\(^{-1}\)) when the model is pointed on the blueshifted side (+3", figure 3.6) and the opposite is seen when the convolving beam is pointed on the redshifted side (velocity bins ~495-745 when the model is pointed at -8", figure 3.7). It would seem that a secondary disk or ring of CO, rotating about a centre offset from that of the primary disk, could explain this result. The centres would need to be offset in order to ensure that the convolving beam "sees" the blueshifted gas when pointed on the redshifted side of the galaxy. There is other evidence for the necessity of a multi-component model for the CO in NGC 5866. Looking at figures 3.5 and 3.8, the "saw tooth" pointings, a secondary peak can be seen in both, located ~100 kms\(^{-1}\) from the systemic velocity of 745 kms\(^{-1}\). These peaks could not be modelled by placing in clouds without producing large spikes in other pointing spectra. Since these secondary peaks correspond to a maximum rotation
rate of \(~100\) kms\(^{-1}\), this cannot be the source of the extra signal seen in figures 3.6 and 3.7. Multiple concentric gas rings in galaxies are not uncommon (Buta & Crooker, 1993) and NGC 5866 may fall into this category. However, it is difficult to accept a second centre of rotation from basic dynamical considerations. An interferometric study of the centre of NGC 5866 is needed to address this issue.

4.1.4 The Molecular Gas Kinematics

The most intriguing feature of NGC 5866 presented in this work is the rapid rotation of the CO compared to the stellar and ionized gas. Kinematically decoupled gas and stars are not uncommon in early-type galaxies. Fisher's data shows \(>40\%\) (at least 4 of 9) of the S0 galaxies detected in [O III] (5007 Å) have gas obviously decoupled from the stars.

Most theories to explain decoupled stars and gas involve some form of interaction with another galaxy, like the ones discussed in section 4.3 and 4.4 (Bertola et al. 1992, Fisher, 1997), but the differing rotation curves can be accounted for in some cases by a bar, warp or non circular motion (Fisher, 1997), all of which can form internally. The question of why there is an apparent difference between the kinematics of the molecular and ionized gas in NGC 5866 is harder to explain. Since the young stars that ionize the gas form from the molecular gas, it is hard to understand how the two gas components could rotate separately.

The rotation curve used in this work was not measured, but only suggested by the CO data. It is argued in section 3.2.1 that the adopted rotation curve is probably correct to
first order since the CO spectra suggest little velocity dispersion and models using the ionized gas and stellar rotation curves, with and without velocity dispersion, clearly fail to match the data (figures 3.22-3.29). Unpublished interferometry confirm that the CO rotates in excess of 300 km s$^{-1}$ (Wang & Hui, 1994, private communication). Fisher cautions that the ionized gas may indeed be rotating faster than indicated by the [O III] measurements since the [O III] measurements along the major axis do not go out as far as the stellar measurements. Therefore, the [O III] data might not be reliable for modelling the CO kinematics. That fact would not be unprecedented. Prada et al. (1996) report Brγ (2.1661 μm) and H$_2$ 1-0 S(1) (2.1218 μm) observations of the highly inclined, late type spiral, NGC 253 motivated by an apparent discrepancy between the kinematics suggested by CO (Canzian, Mundy & Scoville, 1988) and optical [N II] (6584 Å) data (Ulrich, 1978). The CO rotation curve of NGC 253 is 7 times steeper than the optical rotation curve, much like that seen in figure 3.21 for NGC 5866. The assumption of Prada et al. is that the dust in NGC 253 is obscuring the optical radiation and producing a flattened rotation curve. Essentially, the extinction by the dust at optical wavelengths causes the line-of-sight velocity distribution to measure gas that is at large radii and at some azimuth instead of along the radius assumed from the major axis offsets. The near IR measurements confirm the CO data results (Prada et al., 1996). This effect has been seen in NGC 2146 (Prada et al., 1994) and in NGC 4565 (Sofue et al., 1998).

The [O III] emission from NGC 5866 probably suffers similar extinction due to its prominent dust lane. Near IR measurements might reconcile the ionized and molecular
gas kinematics. Even so, the gas is still rotating on the order of 100 km/s faster than the stars, and any theory for the origin of the gas in NGC 5866 needs to account for this.

4.2 An Internal Origin for the Cool Interstellar Medium

4.2.1 Interstellar Matter Mass Return and Consumption

The measured molecular gas mass of NGC 5866 is $4.55 \times 10^8 \, M_\odot$, which gives a cool ISM mass of $M_{\text{ISM}} = 6.4 \times 10^8 \, M_\odot$ after scaling by a factor of 1.4 to include Helium (10% by number). This value is essentially the same as that found by the mass return calculation (Faber & Gallagher, 1976, Peimbert, 1993), $\sim 10^9 \, M_\odot$, not factoring any star formation. The current star formation rate as derived from the Hα luminosity suggest that mass balance can be maintained, since no more gas is being used to form new stars than is being returned. From this standpoint it would seem that NGC 5866 has evolved as a closed box, retaining most of its returned gas.

In a closed box scenario the large value of $M_{\text{H}_2}/M_{\text{HI}}$ might be due to the dust in NGC 5866. The large amount of dust, suggested by the low gas to dust ratio, provides the perfect environment to create $\text{H}_2$ out of a reservoir of HI since it acts as both a shield from UV radiation and catalyzes surface reactions which form the molecular phase. The relatively low SFR of NGC 5866 also means that the amount of dissociating radiation is low since there are not many young OB stars. On the other hand, a totally molecular ISM is not a clear sign of closed box evolution (Elmegreen, 1993) and looking at the $\text{H}_2$ surface density it seems that NGC 5866 has probably not converted all of its atomic
hydrogen into the molecular phase. Also, a mix of HI and dust does not necessarily produce H₂, but is only a requirement for creating the molecular gas.

4.2.2 Cooling Flows and Molecular gas

Other evidence is consistent with closed box evolution. NGC 5866 has an X-ray corona (Pellegrini, 1994). X-ray emission from galaxies can arise from point sources, such as X-ray binaries, or an extended hot ISM. Cooling flows are hot "streams" of returned gas from evolved stars which are trapped in the galaxy's potential well and cooled by X-ray emission. Once this material is cool enough it can form molecular gas. D'Ercole & Ciotti (1998) performed simulations in order to follow the evolution of gas initially heated to X-ray temperatures by type II supernovae explosions within an S0 galaxy. Simulations with a time decreasing type I supernova rate form gas flows which initially move outward but reverse in direction at the galactic polar regions as the supernova rate declines. Cold filaments, which form at the interface between outflowing and inflowing gas, eventually form cold disks in the galactic centre. If this is the case in NGC 5866 it might explain any off axis detections of gas, presumably from the polar regions, and why the gas is decoupled from the stars, and so close to the centre of the galaxy.

However, the cooling flow model presents a problem for the creation of molecular gas. X-ray radiation destroys the dust necessary to form H₂ and so the molecular gas can only form after the hot ISM has cooled below X-rays temperatures. Also, analysis of ROSAT data (Pellegrini, 1994) indicates that most of the X-ray emission from NGC 5866 mostly likely comes from a population of X-ray binaries rather than a hot ISM.
4.3 An External Origin for the Cool Interstellar Medium

There are several lines of evidence that do not support the closed box evolution theory. The present observations clearly show that the molecular ISM is rotating, but much more rapidly than the stars. Similar conclusions have been reached by Wang & Hui (1994) from unpublished interferometry. Has the gas been captured? If so, the fact that we have found almost as much gas as expected from stellar mass return would appear to be just an odd coincidence. The fact that NGC 5866 has a dust lane tilted by $5^\circ$ with respect to its optical major axis (Bertola et al. 1992) is often quoted as evidence for a past interaction (Burbidge & Burbidge, 1960, Bertola et al., 1992, Pellegrini, 1994). If, indeed, NGC 5866 interacted in the past, the kinematically decoupled gas and stars are potentially a result of this. Based on the number of galaxies which show counter-rotating gas, Bertola et al. (1992) claim that 40% of S0s have acquired their ISM. Counter rotating gas is hard to explain in a closed-box scenario, where most of the gas we see should have come from stars and therefore should share their angular momentum.

4.3.1 Interactions

A merger with one or more smaller satellites could have provided NGC 5866 with its gas. During the cannibalization process, the gas and the stars of the smaller galaxy are affected in different ways. Stars are only affected by the total gravitational field, since stellar collisions are unimportant. However, gas clouds suffer dissipational collisions which cause gas to accumulate in a disk near the centre of the larger galaxy (Ibata, 2001 for example). A merger, therefore, seems like a good option for explaining the molecular gas kinematics.
Another form of interaction is galaxy harassment. "Galaxy harassment" involves interactions between 2 galaxies but without the exchange of material, necessarily. The theory was developed as an alternative to ram pressure stripping for converting later type spirals into early-types within rich clusters. It is a more general mechanism since it doesn't require the presence of an intergalactic medium. Harassment occurs when two galaxies pass close to one another. It is a good candidate to describe the nature of the ISM in NGC 5866 since it predicts that the stars will be unaffected (Icke, 1985), explaining the difference in the gas and stellar kinematics.

Simulations have shown that the required minimum separation is \( \sim 20-50 \) kpc to be effective, depending on the mass of the intruder and the relative velocity (Icke, 1985, Moore et al. 1995). Moore et al. (1995) modelled a cluster environment with galaxies of equal mass in order to follow morphological changes over several billion years. They found that a spiral needs \( \lesssim 5 \) high velocity interactions to force morphological evolution, but did not investigate the fate of the ISM. Icke (1985) investigated how the gas behaves in a flyby scenario, finding that, under the proper conditions, only one interaction was necessary to convert a normal spiral into an S0. An important requirement was that the encounter must boost the gas velocity above the sound speed, but not above the mean velocity of the stars (i.e. less than the stellar velocity dispersion plus the rotational speed). Icke (1985) modelled interactions between galaxies with various mass ratios and concluded that a mass ratio larger than 1/5 is needed at a minimum distance of 20 kpc to induce a shock in the gas without affecting the stars. Under these conditions the gas located between the subject galaxy's centre and the centre of mass of the two body
system migrated inward, while gas on the other side of the centre of mass drifted outward. Icke's work might explain why molecular gas is found near the centre of NGC 5866, whereas HI, which is more widespread in galaxy disks, has not been detected.

Icke's simulations show that the infrared luminosity produced by the star burst created by the shocked gas is on the order of that seen in galaxies observed by IRAS. This might present a problem for NGC 5866, since its present FIR luminosity implies SFR < 2.4 $M_\odot$/yr, much lower than the 40 $M_\odot$/yr predicted by Icke (1985). If the harassment took place ∼1 Gyr ago then the star formation might have dropped to its present rate from a much higher initial value. The low $L_{\text{FIR}}/L_{\text{B}}$ ratio is consistent with this kind of scenario. Another problem is the separation of the NGC 5907 group members. The projected distances of the NGC 5907 group and their relative velocities would seem to negate any chance of multiple interactions, if NGC 5866 was a spiral converted to an SO via the Moore et al. (1995) mechanism. Perhaps a comparison of star formation histories of the NGC 5907 group galaxies might provide a clue as to whether any of them might have "harassed" NGC 5866 in the past. The minimum amount of time possible since an interaction with any of the larger 5907 group members is ∼4 Gyr based on their projected distances and relative velocities. This does not eliminate the possibility of interaction with fainter, undetected nearby galaxies.

4.4 The Local Environment

Since NGC 5866 shows signs of a potential interaction in the past, it is useful to look at other group members in order to establish if, indeed, interactions can and do take place in
the local environment. Other group members may show similar signs of interaction or present more convincing evidence. If this is the case, then an external origin for the gas in NGC 5866 would seem more plausible.

4.4.1 The NGC 5907 Group

Most S0s are found in environments much denser than that of the NGC 5907 group. The local density is defined as the number of galaxies brighter than $M_v = -16$ within a volume 0.5 Mpc per side (Tully, 1988). For example, the local density near the S0 galaxy NGC 4710, a Virgo member found on the outskirts of the cluster, is 2.00 Mpc$^{-3}$, whereas that near NGC 5866 is 0.24 Mpc$^{-3}$. The $M_{\text{H}_2}/M_{\text{HI}}$ mass ratio in NGC 4710 has a $M_{\text{H}_2}/M_{\text{HI}} \approx 30$ whereas for NGC 5866 $M_{\text{H}_2}/M_{\text{HI}} \approx 3.5$. It is not surprising to find higher $M_{\text{H}_2}/M_{\text{HI}}$ mass ratios in higher density areas like rich cluster galaxies since they are in an environment which is known to remove gas either through tidal stripping by other galaxies or by ram pressure stripping (Kenney & Young, 1989, Gunn & Gott, 1972). Both processes raise the molecular to atomic Hydrogen ratio since the HI is more widely distributed within the galaxies and more easily stripped. Interaction and merging are more common in rich clusters due to the large number density of galaxies. Neither ram pressure nor tidal stripping seem likely for NGC 5866, however. The NGC 5907 group probably lacks a dense intra cluster medium like that in the Virgo cluster to strip the gas away, but the group does provide neighbours with which NGC 5866 could interact.
The possibility of galaxy interaction needs to be explored in a more appropriate context than rich galaxy clusters like Virgo or Coma. Table 4.1 gives a list of known galaxies in the NGC 5907 loose group.

Table 4.1 The NGC 5907 group of galaxies. All information is from the Tully Nearby Galaxies Catalogue (1988).

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>R.A.</th>
<th>Dec</th>
<th>Vₘ₀</th>
<th>Distance</th>
<th>D₂₅</th>
<th>log Lₜ</th>
<th>log M_HI</th>
</tr>
</thead>
<tbody>
<tr>
<td>5907</td>
<td>Sc</td>
<td>15 14.6</td>
<td>56 31</td>
<td>666</td>
<td>14.9</td>
<td>11.2</td>
<td>10.41</td>
<td>10.14</td>
</tr>
<tr>
<td>5866</td>
<td>S0</td>
<td>15 5.1</td>
<td>55 57</td>
<td>692</td>
<td>15.3</td>
<td>7.3</td>
<td>10.22</td>
<td>-</td>
</tr>
<tr>
<td>5879</td>
<td>Sbc</td>
<td>15 8.4</td>
<td>57 12</td>
<td>775</td>
<td>16.8</td>
<td>4.5</td>
<td>9.98</td>
<td>9.35</td>
</tr>
<tr>
<td>U9776</td>
<td>Im</td>
<td>15 11.7</td>
<td>57 10</td>
<td>830</td>
<td>17.4</td>
<td>1.1</td>
<td>-</td>
<td>8.46</td>
</tr>
<tr>
<td>U9769</td>
<td>Sdm</td>
<td>15 10.7</td>
<td>55 59</td>
<td>844</td>
<td>17.7</td>
<td>2.9</td>
<td>9.01</td>
<td>9.23</td>
</tr>
</tbody>
</table>

4.4.2 NGC 5907: A Well Studied Neighbour

The most thoroughly studied member of the NGC 5907 group is NGC 5907 itself, a nearly edge on (inclination = 86.5°, Dumke et al., 1997) Sc galaxy. This was the first external galaxy found to have a warped HI disk (Sancisi, 1976), at first considered to be caused by some form of interaction (Hunter & Toomre, 1969). The HI warp is not a definitive sign of interaction, however. Recent studies have shown that a warped disk can form internally through stellar random motions (Sellwood, 1996), differential precession of gas in a non-spherical halo potential (New et al., 1998) or by out flow winds from X-ray binaries or active galactic nuclei (Quillen, 2001). However, despite these internal mechanisms, interaction is still an attractive candidate for producing warps.
in galactic gas disks. Sancisi (1976) mentions NGC 5866 as a possible interactor with NGC 5907 but points out that the event would have happened \( \sim 4 \times 10^9 \) yrs ago based on the projected separation and relative velocity of the two galaxies (84' and \( \sim 100 \) kms\(^{-1} \), respectively). Sancisi used a distance of 18 Mpc for NGC 5907, but adapting 14.9 Mpc does not alter the minimum actual separation enough to significantly change the age of the hypothetical interaction, which is larger than the expected survival time of the warp (Sancisi, 1976, and references therein).

The dwarf galaxy PGC 54419 is only 11'.5 from the centre of NGC 5907 and is situated 3'.7 from the tip of the warped atomic gas (Shang et al., 1998). This object seems like a more plausible candidate than NGC 5866 for the cause of the warp. At a distance of 14.9 Mpc, PGC 54419 is located \( \sim 50 \) kpc away from NGC 5907 and only \( \sim 16 \) kpc in projection from the warp.

Other evidence suggests that NGC 5907 is a cannibal. Lequeux et al. (1998) report that the halo of NGC 5907 is redder than the disk, implying that it is more metal rich. This is unexpected because it is generally believed that halo objects are old and relatively metal poor, like the globular clusters of our own galaxy. Red colours indicate 2\(^{\text{nd}}\) generation, metal rich stars of intermediate age, like our sun, or many, low mass (\( \leq 0.15 \) M\(_{\odot} \)), old, metal-poor stars, more than can be explained using standard IMFs. Lequeux et al. (1998) suggest that the red halo is the remnant of a small, low mass elliptical galaxy which merged with NGC 5907 around 2 Gyr ago. They support their claim with an N-body simulation of a disk galaxy of mass \( 307 \times 10^9 \) M\(_{\odot} \) interacting with a \( 30.7 \times 10^9 \) M\(_{\odot} \)
spherical companion. The simulation starts with the galaxies 32 kpc apart and with the companion in a near circular orbit with a velocity of 200 km s\(^{-1}\). After 1.9 Gyr the parent galaxy has a warped disk, slightly tilted to its original plane. The stars of the smaller galaxy became distributed throughout the parent halo.

Another, less obvious sign of cannibalism is the discovery of a faint stellar ring surrounding NGC 5907 with an inclination of 45° to the plane of the galaxy (Shang et al., 1998), the first of its kind in an external galaxy. Similar stellar streams have been observed in the Milky Way and, recently, a similar discovery has been made on M31 (Ibata et al. 2001), arguing that this phenomena may be common for large galaxies. The ring around NGC 5907, is approximately the same size as the major axis of NGC 5907, and lacks detected gas. The authors propose that the ring is the remnant of a dwarf spheroidal galaxy that has been tidally disrupted by NGC 5907. The lack of detected gas could mean that the former companion itself had little gas, or that the gas has been redistributed throughout the NGC 5907 halo therefore is too tenuous to be seen by the reported observations (Shang et al., 1998). A third possibility is that the gas has been added to that already present in the NGC 5907 disk.

There is thus ample evidence that NGC 5907 has interacted with other galaxies, making it not unreasonable to assume that NGC 5866 has done so also. The interstellar media of NGC 5907 and NGC 5866 share properties which suggest similar histories. Sofue (1994) reports that the molecular gas in NGC 5907 is located predominantly in the central 5 kpc region, in a ring-like distribution, similar to the molecular rings of M31, and also NGC
5866. A CO study by Garcia-Burillo et al. (1997) of the nuclear region of NGC 5907 finds that the molecular gas is rotating at $\pm 180$ km s$^{-1}$ in the inner 10" and that the CO brightness distribution is asymmetrical. Both of these findings are similar to those found for NGC 5866 in this work. Garcia-Burillo et al. claim that a portion of the molecular gas may be counter rotating; could this be the missing gas from the stellar ring found by Shang et al. (1998)? Due to the kinematical similarities between NGC 5866 and NGC 5907, and along with other corroborating evidence, such as the tilted dust lane, it is plausible to assume that NGC 5866's paucity of HI and its molecular gas kinematics can be explained by previous interaction.

In summary, it seems likely that the bright members of the NGC 5907 group have experienced gravitational interactions in the past. Indeed, even our own galaxy exhibits many of the same features indicating interaction, such as an HI warp and streams of cannibalized stars. These events are probably quite common even in relatively low density environments, and NGC 5866 has not been immune to them.

4.5 Conclusions

NGC 5866 is a gas rich lenticular galaxy, having the majority of its cool interstellar medium in the form of molecular gas. The gas appears to occupy a broken ring structure with several hot spots similar in size and mass to the giant molecular clouds of the Milky Way. The overall picture presented by the data is that NGC 5866 has retained much of the gas returned by its stars. The most reliable star formation rate, inferred from the H$\alpha$ luminosity, implies that the interstellar medium is in mass balance. The S0 galaxy class
exhibits wide ranging values for any measurable or inferred quantity and so, on the whole, NGC 5866 appears fairly typical. There are several areas which need further study in order to confirm the former statement. The strange features in the spectra which could not be synthesized by the simple model used here, such as the extra signal seen in the 0,0 and 9-7 pointings (figures 3.6 and 3.7) need to be looked at again. An interferometric study of the nuclear region of NGC 5866 would provide the necessary resolution to ascertain the true nature of these anomalies. Also, the rotation of the ionized and molecular gas needs to be reconciled; a near IR study of NGC 5866 would be useful for this purpose. If near IR observations confirm the ionized gas rotation curve then much more study needs to be done on this galaxy in order to understand how the two components could be separated.

It is interesting that NGC 5866 should have roughly the amount of gas predicted by simple mass return arguments, yet still show many signs which indicate that it has gained or lost gas. Although the mass balance found here is intriguing, the simple nature of the calculation does not allow for solid conclusions. The fact that the molecular gas appears to be kinematically decoupled from the stars, that the $M_{\text{HI}}/M_{\text{H}_2}$ mass ratio is higher than average, and that the dust lane is tilted, lead one to believe that the molecular gas in NGC 5866 is of external origin. The major arguments for an external origin of the gas is the rapid rotation of the molecular gas compared to the stars and the tilted dust lane. Even if the ionized gas is rotating in the same fashion as the molecular gas, the fact that the gas is rotating faster than the stars still poses a problem for any internal origin theory. This is compounded by the statistical results showing that gas is accreted onto lenticulars in a
substantial fraction of the cases observed (Bertola et al., 1992). The kinematics suggest that if some form of interaction took place, it most likely happened on the order of 1 Gyr ago based on the evidence of a higher SFR in the distant past and the fact that there is no smoking gun left over from the event like a clear morphological distortion.

A search for potential companions would be useful, since any smaller galaxy found nearby might provide clues to the origin of the ISM in NGC 5866, should the companion show signs of interaction. Since the stellar rotation curve of Fisher (1997) shows no sign of two kinematically distinct major stellar populations, a recent major merger with another galaxy does not seem plausible, but this does not rule out cannibalization of an intergalactic cloud or smaller companion such as a gas-rich dwarf. If an accretion event has taken place then NGC 5866 should show other signs like those found in NGC 5907. Since it is edge on it should not be difficult to perform a colour analysis of its halo to see if it too exhibits the same red colour of NGC 5907. Signs like stellar streams or shells are hard to find in a distant galaxy but it has been done for NGC 5907. Again, a detailed colour analysis of off axis regions may prove fruitful in finding an independent population of stars. The fact that the detected ISM is molecular discounts accretion from a companion since most dwarf galaxies, like our Magellanic clouds, appear to be HI rich. Another line of tests might be to take a closer look at the nuclear region of NGC 5866. A more detailed kinematic map of the molecular gas would surely provide more clues as to its origin. A high sensitivity search for HI might prove useful as well. Perhaps the HI kinematics could corroborate any origin theory for the cool ISM.
Given the local environment, galaxy harassment might be the best option, since it does not require a merger but only a close encounter. This scenario is the most compatible with the results. The harassment would have taken place \(-1\) Gyr ago, as argued above. The HI at larger radii was stripped away, raising the molecular to atomic hydrogen ratio and leaving the remaining gas perturbed, rotating faster than the unaffected stars. The perturbation left the gas in a ring-like structure and caused a starburst episode in which the star formation rate declined to the present rate consistent with the low present day FIR luminosity to blue luminosity ratio. Since the cool ISM mass is so close to the value obtained from mass return arguments this might mean that NGC 5866 did not have very much atomic hydrogen in the first place or that the harassment simply caused the atomic hydrogen to be converted into \(H_2\) via a pressure increase. This scenario would leave other traces that could still be found today. During the starburst period, the star formation rate would be \(-40\, \text{M}_\odot/\text{yr}\) (Icke, 1985). Assuming a relatively long starburst episode of \(-100\) Myr, approximately 1% of the stars in NGC 5866 would be a result of this starburst period. Any stars formed at this time would not be decoupled from the molecular gas since the gas that they formed out of was already perturbed. A very careful search for this population might prove fruitful.
Chapter 5

Summary

In this work the cool ISM of NGC 5866 is investigated through the analysis of multiple pointing $^{12}$CO J=1-0 data. Several solid conclusions can be made about the molecular ISM from these data. The results are summarized in point form below.

1. The molecular Hydrogen mass is found to be $4.55 \pm 0.43 \times 10^8$ $M_\odot$ which reveals a cool ISM mass of $\sim 6.4 \times 10^8$ $M_\odot$ when the molecular gas mass is scaled up to include Helium.

2. The molecular gas in NGC 5866 is distributed asymmetrically in a broken Gaussian ring with a radius of $\sim 1.1$ kpc. Giant molecular clouds, analogous to those found in the Milky Way are inferred to be located mostly on the redshifted side of the galaxy space.
3. The molecular gas is rotating rapidly with a maximum rotation speed of 305 kms\(^{-1}\). This is on the order of 100 kms\(^{-1}\) faster than previously published rotation speed values for the stars and the ionized gas in NGC 5866 (Fisher, 1997).

4. The gas appears to be in mass balance based on a mass return rate of \(-0.1\) M\(\odot\)/yr and a gas consumption rate via star formation of \(-0.047\) M\(\odot\)/yr.

5. Several lines of evidence point to an external origin for the molecular gas. A high value of \(M_{\text{HI}}/M_{\text{HII}} = 3.5\), kinematically decoupled stars and gas, evidence for a larger star formation rate in the past and the tilted dust lane all point to an external origin of, or at least influence on, the cool ISM.

6. The observed and inferred properties of the cool ISM can be consistently explained by a galaxy harassment event on the order of a billion years ago.

7. Future work should include an interferometric study of the nuclear region in order to pin down the source of the strange, unexplained spectral features along with near IR observations. The near IR observations are also needed to reconcile the molecular and ionized gas kinematics. Careful photometric study of the stars and a high sensitivity search for faint companions might also provide corroborating evidence to any external origin theory.
Appendix A

COSPEC Source Code

The following lists the COSPEC source code, written in FORTRAN. The line numbers were added to the code in this appendix in order to reference different parts of the code in appendix B. COSPEC was originally written by D. Welch and G. Welch for work on the lenticular galaxy, NGC 4710, and was later extensively modified by the author for work on NGC 5866. Many of the modifications were made to make the program universal and not exclusive to any one particular object. The only remaining parameter which needs to be changed in the source code for future work is the velocity dispersion relation to radius (lines 649 only). This relation is specific to NGC 5866. The continuous numbers aligned to the left are used as a reference in appendix B. Numbers referred to in the body of the code are independent of the numbers to the left.
PROGRAM COSPEC  AUGUST 31 2001

C Written by: D. Welch in JAN 1993
C Modified by G. Welch in APR 1993 to incorporate up to 10 cloud complexes which are brighter than surrounding disk. These complexes are referred to as "clouds".
C
C Modified by A. LeBlanc in 2000/2001. The program has been made more general for work on the S0 galaxy NGC 5866, but is not specific to it. The program now allows for different sized disks or rings (input in "") with various different intensity profiles. The 'IRAM 30m telescope' PP can be pointed anywhere along the major axis, or at an angle to the major axis for either the CO J=2-1 or CO J=1-0 transition. Other additions include a graphing subroutine creates a spectra using pgplot, a variable rotation curve, multiple pointing data, variable cloud sizes and a velocity dispersion component.
C
C Purpose: To model the profile of CO emission line produced by an inclined rotating thin disk or ring.
C
C Comments: The disk has radius ROUTER, is viewed at angle TIP relative to its face. It is assumed that the disk comprises a large number of optically thick CO clouds. No cloud shadows another, so all clouds are seen regardless of the tip angle of the disk.
C
C UNITS: The internal distance unit is the "cu" = COSPEC unit.
C The radius of the disk is set at 100 cu. Angles in degrees.
C
C INTEntITIES: The intensity unit is the central intensity of the disk.
C
C This program is called by typing:
C f77 -o 'currentname' pgplot, which displays the output. It must be compiled 'currentname'.f -lpplot -lx11
C
C **********************************************************
C
C Array RINOBS will hold the intensity for each bin of DVEL km/s width for a total velocity range of + or - DVEL*200 km/s.
C
C
C EXTERNAL TELSENS, FUNCTION1
REAL RINOBS (410), RVEL, RCLoud(10,3), AZcloud(10,3)
REAL RINTCL(10), RVELG (410), RING
REAL FUNCTION1, CLEDGE(20)
REAL RINOBSG (410), RVELG2 (410), RINOBSG2 (410)
REAL CONV, ARCDISC, OFFSET, AZCE, TRUNC, TOP
REAL TURNVEL, TURNRAD, TURNRADCu, FWHM, GRR, LBASE, CLH
REAL SEED1, SEED2, GAUSSDEV, VDIS, NORM
REAL CLSIZE (10)
LOGICAL NOSHIFT, AZBACK, AZAHED, BEAM, TRANS21, DISK
LOGICAL VD, CLOUDS, RINGS, ROTCUR
CHARACTER NEXT, MODEL, DISKMOD, RINGMOD, PICPICK
CHARACTER*12 FILENAME
CHARACTER*80 TEXT
INTEGER*2 IRAD, I, J, IVEL, INUM, IFIRST, ILAST, ISTART
INTEGER IDC(IO), IC(20), N, T, M, B, O, G

C Ask for input data.

C The following constitute the standard parameters:

C Note that the exponential scale length, DS, is expressed
C as a fraction of the disk radius, whereas the FWHM used in
C Gaussian profiles is expressed as a fraction of the disk
C diameter.

C

TIP = 90 ! 90 degrees for edge-on disk
TOP = 0 ! angle the PPcenter to the disk major axis
VELCON = 305 ! rotational velocity at disk edge (km/s)
VELOBJ = 745 ! systemic velocity (km/s)
CLOUDS = .FALSE. ! including clouds or not, default in no
BEAM = .TRUE. ! power pattern on or off, default is on
ARCDISC = 60 ! disk diameter ("
OFFSET = 0 ! PP offset from the centre disk major axis ("
TRANS21 = .FALSE. ! transition, default is CO J=1-0
TURNVEL = 200 ! the kink vel. in the rot. curve (km/s)
TURNRAD = 10 ! the kink radius in the rotation curve ("
DISK = .TRUE. ! disk model? default is yes
RINGS = .FALSE. ! ring model (R.M.)? default is no
DVEL = 10.4 ! spectrum bin size (km/s)
VD = .FALSE. ! velocity dispersion default is off
DISKMOD = 'c' ! what kind of disk model, default is constant
RINGMOD = 'c' ! this is the R.M. type
NORM = 22.1 ! area used to normalize the models (T km/s)
ROTCUR = .FALSE. ! display the rotation curve data or not

C the following standard parameters are included so that user
C can change the model type form a constant intensity disk
C and only recompile once. The values below are included as an
C example. When changing the standard model from disk to ring
C DISK must = .FALSE. and RINGS must = .TRUE. The opposite is
C true when changing the model back from a ring to a disk.

C

FWHM = .5 ! FWHM expressed as a fraction of the disk size
GRR = 15 ! Gaussian ring radius, "
DS = .45 ! scale length of (exponential) disk brightness
RING = 15 ! ring radius, constant intensity, "
TRUNC = 10 ! inner radius where Gaussian is truncated, "

C

C ensured that CONV is specified. All input in " rely on CONV to
C convert to computer units.

C

CONV = ARCDISC/200
TURNRADCU = TURNRAD/CONV
N_CLOUD = 0

C

C These lines ensure the proper values are written to the
C screen when changing the standard input model from a constant
C intensity disk.
IF (RINGS) THEN
    FWHM2 = FWHM*CONV*200
    GRR2 = GRR
    TRUNC2 = TRUNC
END IF
IF ((DISK) .AND. DISKMOD .EQ. 'g') THEN
    DS2 = DS*ARCDISC/2
    FWHM2 = FWHM*CONV*200
END IF
C
B, 0 are triggers, later in the code they may become 1 and a
C print is or is not longer called (they are for table headings)
C G is a counter.
C
B = 0
O = 0
G = 0
C
the standard parameters are written to the screen and the user
C may change any of them, more than once (i.e. if a mistake is
C made, simply ask to change the value again) at run time.
C
C
PRINT*, '  '
PRINT*, '  ****************************** I
PRINT*, '  * THE STANDARD PARAMETER SET *  '
PRINT*, '  *****************************
39 IF (O .EQ. 1) Then
PRINT*, '  '  
PRINT*, '  *****************************
PRINT*, '  * THE MODIFIED PARAMETER SET *  '
PRINT*, '  *****************************
ELSE
    CONTINUE
END IF
PRINT*, '  '
IF ((DISK) .AND. DISKMOD .EQ. 'c') PRINT*, 'a) MODEL =
  2 CONSTANT INTENSITY DISK'
IF ((DISK) .AND. DISKMOD .EQ. 'e') PRINT*, 'a) MODEL =
  2 EXP DISK, SCALE LENGTH = ', DS2, '
IF ((DISK) .AND. DISKMOD .EQ. 'g') PRINT*, 'a) MODEL =
  2 GAUSSIAN DISK, FWHM = ', FWHM2, '
IF ((RINGS) .AND. RINGMOD .EQ. 'c') PRINT*, 'a) MODEL =
  2 CONSTANT INTENSITY RING OF RADIUS', RING, '
IF ((RINGS) .AND. RINGMOD .EQ. 'g') PRINT*, 'a) MODEL =
  2 GAUSS RING, RADIUS = ', GRR2, ', FWHM = ', FWHM2, '
IF ((RINGS) .AND. RINGMOD .EQ. 't') PRINT*, 'a) MODEL =
  2 TRUNC. GAUSS RING RADIUS = ', GRR2, ', FWHM = ', FWHM2, '
  INNER TRUNC RAD = ', TRUNC2, '
PRINT*, '  '
IF (CLOUDS) THEN
PRINT*, 'b) CLOUDS? = YES'
ELSE
PRINT*, 'b) CLOUDS? = NO'
END IF
PRINT*, '  
PRINT*, 'c) TIP = ', TIP, ' degrees
2The inclination on the sky'
PRINT*, '  
PRINT*, 'd) TOP = ', TOP, ' degrees
2The angle with respect to the power pattern axis'
PRINT*, '  
PRINT*, 'e) ARCDISC = ', ARCDISC, ' " The disk diameter'
PRINT*, '  
PRINT*, 'f) VELOBJ = ', VELOBJ, ' km/s The systemic
2velocity'
PRINT*, '  
PRINT*, 'g) VELCON = ', VELCON, ' km/s The disk edge
2rotational velocity'
PRINT*, '  
PRINT*, 'h) TURNRAD = ', TURNRAD, ' " Regime change
2 radius in the rotation curve'
PRINT*, '  
PRINT*, 'i) TURNVEL = ', TURNVEL, ' km/s Regime change
2velocity in the rotation curve'
PRINT*, '  
PRINT*, 'j) POWER PATTERN ON? = YES'
ELSE
PRINT*, 'j) POWER PATTERN ON? = NO'
END IF
PRINT*, '  
PRINT*, 'k) OFFSET = ', OFFSET, ' " Power pattern offset. 2If no PP, this is ignored'
PRINT*, '  
PRINT*, 'l) CO transition : J=2-l'
ELSE
PRINT*, 'l) CO transition : J=l-0'
END IF
PRINT*, '  
PRINT*, 'm) DVEL =', DVEL, ' km/s the spectrum bin size'
PRINT*, '  
PRINT*, 'n) VELOCITY DISPERSION ON? = YES'
ELSE
PRINT*, 'n) VELOCITY DISPERSION ON? = NO'
END IF
PRINT*, '  
PRINT*, 'o) AREA USED FOR NORMALIZATION =', NORM, ' T km/s'
PRINT*, '  
PRINT*, 'p) DISPLAY ROTATION CURVE DATA? = YES'
ELSE
PRINT*, 'p) DISPLAY ROTATION CURVE DATA? = NO'
END IF
PRINT*, '  
PRINT*, '  You have made', G, ' changes to the
2parameter set'
PRINT*, ''
PRINT*, '' ****************************************************
2**************:
PRINT*, '' * IF THIS IS FINE, TYPE LOWER CASE "y", IF
2NOT, INPUT THE *
PRINT*, '' *LOWER CASE LETTER NEXT TO THE QUANTITY YOU
2WANT TO CHANGE*''
PRINT*, ' *
2
PRINT*, ' * ---> WARNING: If changing ARCDISC,
2do so first <--- *'
PRINT*, '' ****************************************************
2**************:
READ*, NEXT
IF (NEXT .NE. 'y') G = G + 1
IF (NEXT .EQ. 'a') GOTO 79
IF (NEXT .EQ. 'b') GOTO 12
IF (NEXT .EQ. 'c') GOTO 85
IF (NEXT .EQ. 'd') GOTO 84
IF (NEXT .EQ. 'e') GOTO 57
IF (NEXT .EQ. 'f') GOTO 83
IF (NEXT .EQ. 'g') GOTO 82
IF (NEXT .EQ. 'h') GOTO 86
IF (NEXT .EQ. 'i') GOTO 87
IF (NEXT .EQ. 'j') GOTO 50
IF (NEXT .EQ. 'k') GOTO 89
IF (NEXT .EQ. 'l') GOTO 88
IF (NEXT .EQ. 'm') GOTO 81
IF (NEXT .EQ. 'n') GOTO 77
IF (NEXT .EQ. 'o') GOTO 69
IF (NEXT .EQ. 'p') GOTO 76
IF (NEXT .EQ. 'y') GOTO 56

C
C The size of the disc is input in arc seconds (ARCDISC). This is
C then used to calculate the ratio of arc second to cu (computer
C units, see above). This ratio is CONV ("/cu"). This ratio is
C used throughout in order to convert input value into those that
C can be understood by the program (i.e. it puts everything into
C computer units, cu. This is paramount and is the reason for the
C warning at runtime that if the disk size is going to be changed,
C change it first as many other quantities depend on the value of
C CONV which is dependent on the disk size. The OFFSET is the
C center position of the power pattern. It is in input in
C arc seconds and is input as negative when on the side of the
C center of the disc which is rotating away from the line of
C sight (larger velocities) and it is input as positive (center is 0)
C for an offset on the side of the disc which is rotating into the
C line of sight (lower velocities). These values are used by the
C power pattern function, TELSENS for CO J=2-1 or TELSENS2
C for CO J=1-0.
C
57 PRINT *, 'input the disc size in arc seconds'
READ *, ARCDISC
CONV = ARCDISC/200
E = 1
GOTO 39
89 PRINT*, 'Set offset along the major axis in arcseconds'
READ *, OFFSET
O = 1
GOTO 39
88 TRANS21 = .TRUE.
PRINT*, 'for CO J=1-0 type y, for CO J=2-1 type n'
READ *, NEXT
IF (NEXT .EQ. 'Y' .OR. NEXT .EQ. 'y') TRANS21 = .FALSE.
O = 1
GOTO 39
87 PRINT*, 'input the "kink" velocity (km/s) in the rotation'
PRINT*, 'for no kink input the max. rot. velocity'
READ*, TURNVEL
O = 1
GOTO 39
86 PRINT*, 'input the "kink" radius (") in the rotation curve'
PRINT*, 'for no kink input 1/2 the disk size in "'
READ*, TURNRAD
TURNRADCU = (TURNRAD/CONV)
O = 1
GOTO 39
85 PRINT*, 'Input disk inclination in degrees (0 is face-on)'
READ *, TIP
O = 1
GOTO 39
82 PRINT*, 'Input disk edge rotational velocity in km/s.'
READ *, VELCON
O = 1
GOTO 39
83 PRINT*, 'Input systemic velocity in km/s.'
READ *, VELOBJ
O = 1
GOTO 39
84 PRINT*, 'Input disk inclination in degrees with respect
2to the power pattern axis'
PRINT*, '0 = the power pattern axis and the major axis
2of the disk are aligned'
READ *, TOP
O = 1
GOTO 39
81 PRINT*, 'Input the desired bin size in km/s'
READ*, DVEL
O = 1
GOTO 39
69 PRINT*, 'Input the normalization area in T km/s'
READ *, NORM
O = 1
GOTO 39
76 PRINT*, 'Display the rotation curve data? (y/n)'
READ*, NEXT
IF (NEXT .EQ. 'y') THEN
ROTCUR = .TRUE.
O = 1
GOTO 39
ELSE
GOTO 39
END IF
C Ask about clouds.
C
12  CLOUDS = .FALSE.
PRINT *, 'Include clouds ("y" or "n")?'
READ *, NEXT
IF (NEXT .EQ. 'n' .OR. NEXT .EQ. 'N') THEN
NCLOUD = 0
GOTO 39
END IF
PRINT *, 'Read cloud parameters from disk file ("y" or "n")?'
READ *, NEXT
IF (NEXT .EQ. "y" .OR. NEXT .EQ. "Y") GOTO 20
C
C Accept cloud parameters from the console
C
PRINT *, 'Now input information on any clouds present'
PRINT *, 'Number of clouds (1 - 10)?'
READ *, NCLOUD
IF (NCLOUD .EQ. 0) GOTO 12
IF (NCLOUD .GT. 1) PRINT*, 'Enter in clouds in order of increasing radial position'
DO 15 N = 1, NCLOUD
PRINT *, 'Radial position of cloud', N, 'as a fraction of disk radius?'
READ *, RCLOUD (N, 1)
PRINT *, 'Azimuth of this cloud in degrees (0 - 360)?'
READ *, AZCLOUD (N, 1)
PRINT*, 'Intensity of this cloud? (centre has unit int.'
READ *, RINTCL (N)
PRINT*, 'Input cloud size in cu. Disk is 100 cu in'
READ *, CSLSIZE (N)
GOTO 16
15  READ *, CLSIZE (N)
GOTO 16
16  IF (NCLOUD .GT. 0) CLOUDS = .TRUE.
PRINT*, 'Display a picture of the cloud positions? (y/n)'
READ*, PICPICK
IF (PICPICK .EQ. 'y') THEN
CALL CLOUDPIC(NCLOUD, CLSIZE, RINTCL, RCLOUD, AZCLOUD)
O = 1
GOTO 39
ELSE
O = 1
GOTO 39
END IF
C
C Read cloud parameters from existing disk file "clparam.dat"
C
C Below is an example of how "clparam.dat" should be set up in C order to work. Assume that the Cs are the edge of the text box.
C NUMBER OF CLOUDS ON NEXT LINE
C RCL OUD AZCLOUD RINTCL CLSIZE
 .5 91 0 10.0
 .5 79 0 10.0
 .18 0 2 12.0
 .1 180 2 6.6
 .28 180 7 7.0
 .72 180 3 9.0
 .9 139 0 20.0
 .9 221 0 20.0
 .5 139 0 9.0
 .5 221 0 9.0
 20 FILENAME = 'clparam.dat'
 OPEN (UNIT=8, FILE=FILENAME)
 READ (UNIT=8, FMT=28) TEXT ! Read 1st LINE - not used
 READ (UNIT=8, FMT=29) NCLOUD
 READ (UNIT=8, FMT=28) TEXT ! Read column headings - not used
 PRINT *, ''
 PRINT *, ' There are ', NCLOUD, ' clouds in this file'
 28 FORMAT (A80)
 29 FORMAT (2X, I2)
 GOTO 33
 33 DO 35 N = 1, NCLOUD
 NCL = N
 READ (8,*, END=35) RCL OUD(N,1), AZCLOUD(N,1),
 RINTCL(N), CLSIZE(N)
 35 CONTINUE
 GOTO 42
 C After a successful read, print out the parameters
 C
 PRINT *, ''
 PRINT *, ' THE FOLLOWING CLOUD PARAMETERS WILL BE USED'
 PRINT *, ''
 PRINT *, ' RADIUS AZIMUTH INTENSITY SIZE'
 PRINT *, ''
 DO 44, N = 1, NCLOUD
 PRINT 45, RCL OUD(N,1), AZCLOUD(N,1), RINTCL(N), CLSIZE(N)
 45 FORMAT (2X, F5.3, 4X, F4.0, 6X, F5.2, 4X, F5.2)
 PRINT *, '
 PRINT *, ''
 PRINT *, ' Use these clouds ("y" or "n")?'
 READ *, NEXT
 IF (NEXT .EQ. "n" .OR. NEXT .EQ. "N") GOTO 12
 GOTO 16
 50 PRINT *, ''
 PRINT *, ' Turn on tapering by telescope main beam?
 2"y" or "n". Default is "y" '
 READ *, NEXT
 IF (NEXT .EQ. 'y' .OR. NEXT .EQ. 'Y') THEN
 BEAM = .TRUE.
93

   GOTO 39
   ELSE
   BEAM = .FALSE.
   O = 1
   GOTO 39
   END IF
   C
   C
   79 RINGS = .FALSE.
   DISK = .FALSE.
   PRINT*, 'model a disk (d) or a ring (r) ?'
   READ*, MODEL
   IF (MODEL .EQ. 'D' .OR. MODEL .EQ. 'd') GOTO 51
   IF (MODEL .EQ. 'R' .OR. MODEL .EQ. 'r') GOTO 52
   DISK = .TRUE.
   PRINT*, 'how do you want to model the disk int. profile?'
   PRINT*, 'constant (c), exponential drop off (e),
   2or Gaussian (g) ?'
   READ*, DISKMOD
   PRINT*, DISKMOD
   IF (DISKMOD .EQ. 'e') THEN
   PRINT*, 'Input a fractional scale length'
   READ*, DS
   DS2 = DS*ARCDISC/2
   GOTO 39
   END IF
   IF (DISKMOD .EQ. 'C') GOTO 39
   IF (DISKMOD .EQ. 'g') PRINT*, 'input the FWHM as a
   2fraction of the disk size'
   PRINT*, 'of the disk size, e.g. 0.5'
   READ*, FWHM
   FWHM = FWHM*200
   FWHM2 = FWHM*CONV
   O = 1
   GOTO 39
   RINGS = .TRUE.
   PRINT*, 'how do you want to model the ring int. profile? '
   PRINT*, 'constant (c), Gaussian (g), or truncated
   2Gaussian (t) ?'
   READ*, RINGMOD
   IF (RINGMOD .EQ. 'g') GOTO 53
   IF (RINGMOD .EQ. 'c') GOTO 54
   IF (RINGMOD .EQ. 't') GOTO 53
   PRINT*, 'input the radius at which the Gaussian is
   2centered in ''
   READ*, GRR2
   GRR = GRR2/CONV
   PRINT*, 'input the FWHM as a fraction of the disk
   2size e.g. 0.5'
   READ*, FWHM
   FWHM = FWHM*200
   FWHM2 = FWHM*CONV
   IF (RINGMOD .EQ. 't') GOTO 61
   O = 1
   GOTO 39
   PRINT*, 'input the inner radius of the ring in ''
READ*, RING
O = 1
GOTO 39
61 PRINT*, 'input the inner radius where the Gaussian
2 will be truncated in ''
READ*, TRUNC2
TRUNC = TRUNC2/CONV
O = 1
GOTO 39
C
C
77 VD = .FALSE.
PRINT*, 'Do you want to add a velocity dispersion
2 component? (y/n)'
READ *, NEXT
IF (NEXT .EQ. "y" .OR. NEXT .EQ. "Y") then
GOTO 78
ELSE
GOTO 39
END IF
78 VD = .TRUE.
PRINT*, 'Enter a seed for the random number generator'
READ*, SEED1
PRINT*, 'Enter a 2nd seed for the random number generator'
READ*, SEED2
O = 1
GOTO 39
C
C
56 PRINT *, ' . Busy crunching - be back in a moment.'
C Zero the array which holds summed intensity across line profile.
DO 60 I = 1, 410
RINOBS (I) = 0.0
CONTINUE
60 C Set values for parameters.
61 C DVEL is the velocity width of each bin in the profile.
62 C
63 C DVEL = 10.4
64 C CRVEL1 is the velocity associated with the first stored intensity.
65 C
66 IF (VELCON .GE. TURNVEL) RVEL1 = VELCON - DVEL * 200
67 IF (VELCON .LT. TURNVEL) RVEL1 = TURNVEL - DVEL * 200
68 C Outer radius of disk is 100 cu.
69 C
70 ROUTER = 100.0
71 C
72 C R0 is the disk scale length in cu.
73 C
74 R0 = -DS * ROUTER
75 C
76 C DANG is the angular increment, set to 0.1 degree and
77 C expressed in radians.
DANG = 0.00174533

SINTIP is the sine of the disk inclination angle.

SINTIP = SIND (TIP)

RI0 is the intensity per unit area at the centre of the disk.

RI0 = 1.0

BINAREA = 0

Find radial locations in cu of inner, outer edges of all clouds.

IF (NCLOUD .EQ. 0) GOTO 71

PRINT*, 'cloud', NCLOUD

DO 70 N = 1, NCLOUD

RCENTR = RCL0UD (N,1) * ROUTER

RCL0UD (N,3) = RCENTR + 0.5 * CLSIZE(N)

RCL0UD (N,2) = RCENTR - 0.5 * CLSIZE(N)

70 CONTINUE

71 CONTINUE

Choose number of annuli to make velocity increment DVA times DVEL.

DVA = 0.5

IF (VELCON .GE. TURNVEL) FANN = ANINT (VELCON / (DVA*DVEL))

IF (VELCON .LT. TURNVEL) FANN = ANINT (2(TURNVEL / (DVA*DVEL))

PRINT*, FANN, VELCON, DVA, DVEL

Choose number of annuli to make velocity increment DVA times DVEL.

Make sure that annuli have correct width.

DR = ROUTER / FANN

NANN = FANN

PRINT *, ' annuli of width ', DR, ' in solid body part'

PRINT *, ' annuli of width ', DR, ' in solid body part'

Now sum up intensities in this part of disk.

call pgbegin (0,?'a',1,1) ! sets up pgplot to plot

call pgunv (-250.,250.,-40.,0.,0,1) ! to plot the PP

call pglab ('Ang. Distance','Intensity 2 (dB)','Power Pattern')

DO 300 IRAD = 1, NANN

Calculate the radius to centre of annulus.

RADIUS = IRAD * DR - DR / 2.0

The rotation curve is solid body with allowances for a kink

IF (RADIUS .LE. TURNRADCU) THEN

V = -(TURNVEL/TURNRADCU) * RADIUS
ELSE
V = (-((VELCON - TURNVEL) / (ROUTER - TURNRADCU)) * RADIUS) -
2 (VELCON - (((VELCON - TURNVEL) / (ROUTER - TURNRADCU)) * ROUTER))
END IF

IF (ROTCUR) THEN
IF (B .EQ. 0) PRINT*, ' RADIUS (") ', 'VELOCITY (km/s)'
B = 1
PRINT*, RADIUS*CONV , V
ELSE
CONTINUE
END IF

C this line in the velocity dispersion function. It gives the
C average value of the velocity dispersion at a given radius.
C This is work specific and should be changed and the code
C recompiled based on specific data. The average velocity
C dispersion value is used in a Gaussian random number generator
C (see GAUSSDEV function)

VDIS = 118-(2.93*RADIUS*CONV)

DAREA = RADIUS * DR * DANG

Below are the 5 choices of intensity profile chosen at run time.
From top to bottom the profiles are flat disk, exponential disk,
Gaussian disk, flat ring, Gaussian ring. FUNCTIONS 1-4 can be
found at the end of the code. They make a flat profile into
the specified profile. (note that flat disk has nothing done
C to it i.e. no FUNCTION)

IF (DISK) THEN
IF (DISKMOD .EQ. 'O' OR INTNO = RIO
IF (DISKMOD .EQ. 'e') RINTNO = RIO *
2FUNCTION1(RADIUS, R0)
IF (DISKMOD .EQ. 'g') RINTNO = RIO *
2FUNCTION2(FWHM, RADIUS)
ELSE
IF (RINGMOD .EQ. 'c') RINTNO = RIO *
2FUNCTION3(RING, CONV, RADIUS)
IF (RINGMOD .EQ. 'g') RINTNO = RIO *
2FUNCTION4(FWHM, 2RADIUS, GRR)
IF (RINGMOD .EQ. 't') RINTNO = RIO *
2FUNCTION5(RADIUS, TRUNC, GRR, FWHM)
END IF

C Test for clouds.
IF (N CLOUD .EQ. 0) GOTO 115

C Identify clouds included in this annulus. Use array IDC to
C store locations of any such clouds in arrays R CLOUD, RINTCL,
C AZCLOUD for later use.

WHERE = 0
DO 110 N = 1, N CLOUD
   IF (R CLOUD(N,2) .LT. RADIUS .AND. RADIUS .LE. R CLOUD(N,3)) THEN
      NHERE = NHERE + 1
      IDC(NHERE) = N
   END IF
110 CONTINUE

C
C  IF (NHERE .GT. 0) GOTO 130
C
C No clouds found in this annulus.
115 CONTINUE

C Loop through 3600 angular chunks of current annulus.
DO 120 J = 1, 3600
   REALJ = FLOATI(J)

   C Find component of disk velocity along line of sight.

   C this section of the code adds a velocity dispersion element to
   C the velocity given by the rotation curve. See comments in the
   C GAUSSDEV function

   VDIS2 = VDIS * GAUSSDEV(VD, SEED1, SEED2)
   PRINT*, VDIS2
   V2 = V+VDIS2
   VTOOBS = V2 * COSD(REALJ / 10.0) * SINTIP
   IVEL = INT((VTOOBS - RVEL1) / DVEL)

   C Calculate intensity contributed by this chunk. Factor in
   C the telescope beam if this switch is on. The transition is
   C specified when the program is run. The PP for the CO J= 2-1
   C is factored in by the subroutine TELSENS and the CO J=1-0 is
   C factored in by TELSENS2. See comments in the subroutines.
   RINTEN = RINTNO * DAREA
   IF (TRANS21) THEN
      IF (BEAM) RINTEN = RINTEN * TELSENS(RADIUS, 2 REALJ, TIP, OFFSET, CONV, TOP)
   ELSE
      IF (BEAM) RINTEN = RINTEN * TELSENS2(RADIUS, 2 REALJ, TIP, OFFSET, CONV, TOP)
   END IF

   C Add it to the appropriate bin.
   RINOBS(IVEL) = RINOBS(IVEL) + RINTEN
120 CONTINUE
GOTO 300

C Réintroduction of the cloud code. 1 of 2
C
C Deal with any clouds found in this annulus. First find edges
C of all the clouds in azimuthal direction.
C
DO 140 NH = 1, NHERE
   LBASE = ABS((100*R CLOUD(IDC((NH)),1)) - RADIUS)
   CLH = SQRT(ABS(((0.5*CLSIZE(IDC(NH))) - (LBASE*LBASE)))
   2*0.5*CLSIZE(IDC(NH)) - (LBASE*LBASE))
140 CONTINUE
AZCE = ATAN(CLH/RADIUS)*57.296
AZCLOUD(IDC(NH),3) = AZCLOUD(IDC(NH),1) +
2 AZCE
AZCLOUD(IDC(NH),2) = AZCLOUD(IDC(NH),1) -
2 AZCE
C PRINT *, ' AZCLOUD values for annulus ', IRAD
C PRINT *, AZCLOUD(IDC(NH),2), AZCLOUD(IDC(NH),3)
C PRINT *, ' '

C NOTE: This procedure treats clouds as having the same linear
C extent in azimuth across their radial extent; they are not
C "pie-shaped".

NN = 2*NH - 1
CLEDGE(NN) = AZCLOUD(IDC(NH),2)
CLEDGE(NN+1) = AZCLOUD(IDC(NH),3)
IC(NN) = IDC(NH)
C
C Last statement saves original location of this cloud for
C use in intensity calculation. Now sort contents of array
C CLEDGE to put its entries in order of increasing azimuth.
C This makes it easier to work around the annulus. It is
C assumed that clouds do not overlap.

NOSHIFT = .TRUE.
IF (NHERE .EQ. 1) GOTO 151
DO 150 NH = 1, NHERE
   NE = NHERE - 1
   DO 145 N = 1, NE
      NN = 2*N - 1
      IF (CLEDGE(NN) .GT. CLEDGE(NN+2)) THEN
         T1 = CLEDGE(NN)
         T2 = CLEDGE(NN+1)
         IT3 = IC(NN)
         CLEDGE(NN) = CLEDGE(NN+2)
         CLEDGE(NN+1) = CLEDGE(NN+3)
         IC(NN) = IC(NN+2)
         CLEDGE(NN+2) = T1
         CLEDGE(NN+3) = T2
         IC(NN+2) = IT3
         NOSHIFT = .FALSE.
      END IF
   END DO
   IF (NOSHIFT) GOTO 151
END DO
C
C Fill unused elements of array CLEDGE with large values.
C This enables later recognition of no-more-clouds during
C summation around annulus.
C
IF (NHERE .EQ. 10) GOTO 154
DO 153 M = 2*NHERE+1, 20
C Test for a valid sequence of cloud edge locations in array CLEDGE. The positions should monotonically increase, and C no two should be the same. Check for clouds which hang C over the zero of azimuth. First, does lowest-azimuth cloud C extend across AZ = 0?

154 AZBACK = .FALSE.
155 IF (CLEDGE(1) .LT. 0.0) AZBACK = .TRUE.

C Now does highest-azimuth cloud hang over AZ = 0?

159 AZAHED = .FALSE.
160 IF (CLEDGE(2*NHERE) .GT. 360.0) AZAHED = .TRUE.

C Holler if array CLEDGE is not well-ordered.

200 MUP = 2*NHERE - 1
201 DO 160 M = 1, MUP
162 IF (CLEDGE(M) .GT. CLEDGE(M+1)) THEN !line change:GE to GT
163 PRINT *, ' Problems with cloud locations in annulus',
164 2 IRAD
165 END IF
166 CONTINUE
167 IF(AZBACK .AND. AZAHED) THEN
168 PRINT *, ' First and last clouds in annulus', IRAD,
169 2' seem to overlap'
170 STOP 'CRASH'
171 END IF

C If first cloud overhangs AZ=0 begin summation at its first C edge, at AZ < 0. Change from original code (NINT)

176 OFFSETCL = 0.0
177 IF (AZBACK) OFFSETCL = NINT(CLEDGE(1))

C the above change keeps the angular increments integer values C like the annuli with no clouds. Without it you get slightly C different intensities on a bin by bin basis which should be C the same. Instead of starting at 1 you start at some negative C real angle (i.e. start -22.18, next increment -21.18 etc...) C and so all intensities are slightly different. Same applies C for below

C If last cloud overhangs AZ=0 begin summation just beyond its C trailing edge, at AZ > 0.

180 IF (AZAHED) OFFSETCL = NINT(CLEDGE(2*NHERE)) - 360.0

C Now enter loop to sum around this annulus.

183 NH = 1
184 DO 200 J = 1, 3600
REALJ = FLOATI(J) + OFFSETCL*10.0
VTOOBS = V * COSD(REALJ/10.0) * SINTIP
IVEL = ININT((VTOOBS - RVEL1) / DVEL)
IF (REALJ/10.0 .GE. CLEDGE(NH)) THEN
  IF (REALJ/10.0 .LT. CLEDGE(NH+1)) THEN
    RINT = RINTCL(IC(NH))
    GOTO 170
  ELSE
    RINT = RINTNO
    NH = NH + 2
    END IF
  ELSE
    RINT = RINTNO
    END IF
  170 RINTEN = RINT * DAREA
  GOTO 171
  171 IF (TRANS21) THEN
    IF (BEAM) RINTEN = RINTEN * TELSENS(RADIUS,
      2 REALJ, TIP, OFFSET, CONV, TOP)
    ELSE
      IF (BEAM) RINTEN = RINTEN * TELSENS2(RADIUS, REALJ, TIP, OFFSET, CONV,
        2 TOP)
    END IF
    RINOBS(IVEL) = RINOBS(IVEL) + RINTEN
  200 CONTINUE
  C Program skips to Statement 300 if no clouds present in this
  C annulus.
  C
  300 CONTINUE
  C call pgend
  C
  600 DO 620 I = 1, 410
    ISTART = I
    PRINT*, 'I' , I , 'RINOBS (I)' , RINOBS (I)
    IF (RINOBS (I) .NE. 0.0) GOTO 625
  620 CONTINUE
    PRINT *, 'Whoops, the model line profile is zero - TILT!!'
    GOTO 800
  C
  C Loop through output bins to find where the intensity goes to
  C zero. RVEL holds the actual velocity represented by each bin.
  C
  625 IFIRST = ISTART
    PRINT *, 'IFIRST = ' , IFIRST
    RV1 = RVEL1 + DVEL * FLOATI (IFIRST) + VELOBJ
    PRINT*, RV1 , DVEL ,FLOATI (IFIRST) , VELOBJ
    630 RMAX = 0.0
    N=1
    C
    C The following calculates the spectra (i.e. puts the
    C appropriate intensities in the appropriate velocity bins
    C (lines 635-640). This is first calculated based around an
    C arbitrary maximum intensity (see above).
The graph is then normalized by the constant \( QWERTY \) where \( QWERTY \) is the ratio between the computed area under the curve and the area under the curve of the data. The intensities are rebined after being scaled appropriately (lines 646-647).

\[
QWERTY = 1
\]

\[
635 \text{ DO 640 } I = \text{IFIRST}, 410 \\
640 \text{ CONTINUE}
\]

\[
645 \text{ INUM} = \text{ILAST} - \text{IFIRST}
\]

\[
646 \text{ IF (QWERTY} .EQ. 1) \text{ THEN}
\]

\[
647 \text{ PRINT*, 'NORM COEFF. = ', QWERTY}
\]

\[
648 \text{ PRINT*, 'if normalization is done input the real norm.}
\]

\[
649 \text{ 2coeff, '}
\]

\[
650 \text{ PRINT*, 'if normalizing the input is listed above, reenter}
\]

\[
651 \text{ 2 it'}
\]

\[
652 \text{ READ*, QWERTY}
\]

\[
653 T = 1
\]

\[
654 \text{ DO 647 } I = \text{IFIRST}, 410 \\
655 \text{ IF (RINOB (I} .GT. \text{RMAX}) \text{RMAX} = \text{RINOB} (I)
\]

\[
656 \text{ RVEL} = \text{RVEL} + \text{DVEL} \times \text{FLOATI (I)} + \text{VELOBJ}
\]

\[
657 \text{ RVELG (N} = \text{RVEL}
\]

\[
658 \text{ RINOBSG} (N) = \text{RINOB} (I) \times \text{QWERTY}
\]

\[
659 \text{ BINAREA} = \text{BINAREA} + (\text{RINOBSG} (N) \times \text{DVEL})
\]

\[
660 N = N+1
\]

\[
661 \text{ IF (NEXT} .EQ. \text{'P') PRINT *, RVEL, RINOB} (I)
\]

\[
662 \text{ ILAST} = I
\]

\[
663 \text{ BIGV} = (\text{VELOBJ}^2) - \text{RVELG}(1)
\]

\[
664 \text{ IF (RINOB} (I) \times \text{EQ.} \times 0.0 \times \text{AND. RVEL} \times \text{GT. (BIGV+50))}
\]

\[
665 \text{ 2 GOTO 645}
\]

\[
666 \text{ DO 647 } I = \text{IFIRST}, 410 \\
667 \text{ IF (RINOB} (I) \times \text{GT. RMAX}) \text{RMAX} = \text{RINOB} (I)
\]

\[
668 \text{ RVEL} = \text{RVEL} + \text{DVEL} \times \text{FLOATI (I)} + \text{VELOBJ}
\]

\[
669 \text{ RVELG2} (T) = \text{RVEL}
\]

\[
670 \text{ RINOBSG2} (T) = \text{RINOB} (I) \times \text{QWERTY}
\]

\[
671 \text{ 2} \text{PRINT*, T, RINOBSG2} (T), \text{RVELG2} (T)
\]

\[
672 T = T+1
\]

\[
673 \text{ BIGV} = (\text{VELOBJ}^2) - \text{RVELG2}(1)
\]

\[
674 \text{ IF (RINOB} (I) \times \text{EQ.} \times 0.0 \times \text{AND. RVEL} \times \text{GT. (BIGV+50))}
\]

\[
675 \text{ 2 GOTO 645}
\]

\[
676 \text{ ELSE}
\]

\[
677 \text{ CONTINUE}
\]

\[
678 \text{ END IF}
\]

\[
679 T = T-1
\]

\[
680 N = N-1
\]

\[
681 \text{ LASTN} = N
\]

\[
682 \text{ PRINT *, 'LASTN= ', LASTN, ILAST, BINAREA}
\]

\[
683 \text{ PRINT *, 'There are ', INUM, ' intensities of interest'}
\]

\[
684 \text{ PRINT *, 'The maximum intensity is ', RMAX}
\]

\[
685 \text{ 800 PRINT *, ''}
\]

\[
686 \text{ PRINT *, 'SHOW VALUES/GRAPH MODEL (S),}
\]

\[
687 \text{ 2"GOODNESS"/GRAPH DATA&MODEL (G), DONE (D)'}
\]

\[
688 \text{ 810 READ *, NEXT}
\]

\[
689 \text{ C IF (NEXT} .EQ. \text{'A'} \times \text{.OR. NEXT} .EQ. \text{'a'}) \text{ GOTO 10}
\]
IF (NEXT .EQ. 'S' .OR. NEXT .EQ. 's') GOTO 820
IF (NEXT .EQ. 'G' .OR. NEXT .EQ. 'g') GOTO 819
IF (NEXT .EQ. 'D' .OR. NEXT .EQ. 'd') GOTO 1000
PRINT *, 'TRY AGAIN'
GOTO 810

C
C Show the velocities and intensities.
C
819 CALL RMSCALC (LASTN, RVELG2, RINOBSG2, BINAREA, DVEL)
GOTO 800
820 PRINT *, 'LASTN= ', LASTN
CALL GRAPHX (LASTN, RVELG2, RINOBSG2, BINAREA, DVEL)
GOTO 800

C
C Write results to a file.
C
900 FILENAME = 'cospl.dat'
905 OPEN (UNIT=8, FILE=FILENAME, FORM='FORMATTED',
2STATUS='NEW', ERR=910, IOSTAT=IOS)
90 910 IF (IOS .NE. 117) GOTO 920
PRINT *, 'A FILE OF THAT NAME ALREADY EXISTS'
PRINT *, 'INTENDED TO WRITE INTO cospl.dat',
PRINT *, 'PLEASE INPUT ANOTHER FILE NAME'
READ *, FILENAME
GOTO 905
920 PRINT *, 'ERROR OPENING THE FILE, IOS = ', IOS
GOTO 800
930 RNUM = FLOATI (INUM)
WRITE (UNIT=8, FMT=932, ERR=935, IOSTAT=IOS)
932 FORMAT (F6.2, F6.2, F8.2)
WRITE (UNIT=8, FMT=93 3, ERR=935) TIP, FRACR, VELCON, VELOBJ
933 FORMAT (F6.1, F6.2, F6.1, F8.1)
GOTO 940
935 PRINT *, 'ERROR WRITING FIRST DATA, IOSTAT = ', IOS
GOTO 800
940 DO 950 I = IFIRST, ILAST-1
WRITE (UNIT=8, FMT=952, ERR=955, IOSTAT=IOS) RINOBS (I)
950 CONTINUE
952 FORMAT (F10.2)
GOTO 960
955 PRINT *, 'ERROR WRITING RINOBS DATA, IOSTAT = ', IOS
960 CLOSE (UNIT=8)

C
C The program is finished. Get ready to return to main procedure.
C
1000 STOP 'COSPEC done'
END

C
C This subroutine calculates the projected distance of the
C current disk chunk from the disk centre, then computes the
C value of the normalized main beam power pattern at this distance from beam centre.

For IRAM 30m CO (J=2-1), the main beam is a Gaussian with FWHM = 10.5". See Greve et al. 1998, A&ASS, 133, 271 for details on PP calculation.

\[
\begin{align*}
X1 &= RADIUS \times \cos(REALJ/10) \quad \text{gives position in XY plane} \\
Y1 &= RADIUS \times \sin(REALJ/10) \\
XPRIME &= X1 \quad \text{gives position on plane of sky} \\
YPRIME &= Y1 \times \cos(TIP) \\
XNOT &= OFFSET/CONV \quad \text{defines PP center in sky plane} \\
YNOT &= 0
\end{align*}
\]

DIS = SQRT((XPRIME \times XPRIME) + (YPRIME \times YPRIME))

\[
\begin{align*}
\text{IF} \ (XPRIME \ \text{LT.} \ 0) & \quad \text{DIS} = -DIS \\
\text{IF} \ (XPRIME \ \text{EQ.} \ 0) & \quad XANG = 0 \\
\text{IF} \ (XPRIME \ \text{NE.} \ 0) & \quad XANG = \text{ATAN}(YPRIME/XPRIME) \times 57.296
\end{align*}
\]

\[
\begin{align*}
\text{ANGLE} &= \text{TOP} + XANG \\
XPRIME2 &= DIS \times \cos(\text{ANGLE}) \\
YPRIME2 &= DIS \times \sin(\text{ANGLE}) \\
XSIDE &= XPRIME2 - XNOT \quad \text{3 lines calc. dist. fr. PP centre} \\
YSIDE &= YPRIME2 - YNOT
\end{align*}
\]

PPMAX = SQRT((XSIDE \times XSIDE) + (YSIDE \times YSIDE))

ARCSQ = (PPMAX*CONV) * (PPMAX*CONV) ! conv. to " and squares

SIDE1 = ((\text{EXP}(-\text{SIDEARC}/15625)) \times 0.005 ! calc. contribution

SIDE2 = ((\text{EXP}(-\text{SIDEARC}/32400)) \times 0.001 ! from the error

SIDE3 = ((\text{EXP}(-\text{SIDEARC}/902500)) \times 0.00009 ! beams (see ref.)

SIDES = SIDE1 + SIDE2 + SIDE3 ! adds up error beams

TELENS = (\text{EXP}(-\text{ARCSQ}/39.76)) + SIDES \quad \text{calculates PP}

RETURN

This subroutine calculates the projected distance of the current disk chunk from the disk centre, then computes the value of the normalized main beam power pattern at this distance from beam centre.

For IRAM 30m CO (J=1-0), the main beam is a Gaussian with FWHM = 20.7". See Greve et al. 1998, A&ASS, 133, 271 for details on PP calculation.

\[
\begin{align*}
X1 &= RADIUS \times \cos(REALJ/10) \quad \text{gives position in XY plane} \\
Y1 &= RADIUS \times \sin(REALJ/10) \\
XPRIME &= X1 \quad \text{gives position on plane of sky} \\
YPRIME &= Y1 \times \cos(TIP) \\
XNOT &= OFFSET/CONV \quad \text{defines PP center in sky plane}
\end{align*}
\]
SUBROUTINE GRAPHX (LASTN, RVELG2, RINOB2G2, BINAREA, DVEL)

This subroutine plots the spectra using pgplot.

INTEGER LASTN
REAL RVELG2 (410), RINOB2G2 (410)

CALL PGBEG (0, '?', 1, 1)
CALL PGPAGE
CALL PGVSIZ (1.5, 6.5, 1.5, 3.75)!
CALL PGSWIN (100., 1200., -0.02, 0.12)!
CALL PGBOX ('BCNST', 0.0, 0, 'BCNST', 0.0, 0)
CALL PGLAB ('velocity', 'intensity', 'Simulated CO Spectra')!
PRINT *, 'LASTN=', LASTN
PRINT *, 'VELOCITY INTENSITY BIN AREA'
DO 999 T = 1, (LASTN)
PRINT *, RVELG2 (T), RINOB2G2 (T), ((RINOB2G2 (T)) * DVEL)
call pgbin (LASTN, RVELG2, RINOB2G2, 1)
CONTINUE

SUBROUTINE RMSCALC (LASTN, RVELG2, RINOB2G2, BINAREA, DVEL)
This subroutine compares the model and data bin by bin and produces a measure of how well they match called the goodness of fit parameter, GOOD. The user enters a range of velocities over which the comparison is done. The subroutine finds which bins are the same in the model and the data file (it can be another model the file is set up the same as the data files) and subtracts one intensity value from the other (same velocity bin) and squares this number. The goodness of fit parameter takes the square root of the total of the intensities differences squared and subtracts off the uncertainty in the data (user input at run time, varies with pointing) and multiplies this new value by the velocity range covered and divides by the area under the observed data over the same velocity range. A goodness of 0 is best as that would mean there were no differences between the data and the model.

REAL VELOCITY(500), INTENSITY(500), IGNORE(500), DIFF
REAL RVELG2(410), RINOBG2(410), RMS(500), HIGHV, LOWV, INT
REAL VELOCITY2(500), INTENSITY2(500), MODLOW, MODHIGH, RMS1
REAL RINOBG3(500), GOOD, TOTINT, CLARMS

CHARACTER VALUE
CHARACTER*20 DATA
INTEGER Q,Y,T,P,NUM,L

C C enter the data file name
1170 C
1171 PRINT*, 'Input the file name for the pointing in question'
1172 READ*, DATA
1173 OPEN (UNIT=01, FILE= DATA)
1174 C reads in the data from the file
1175 C
1176 C
1177 Y=0
1178 DO 777 Q=1,500
1179 READ (01,*,END=779) VELOCITY(Q), INTENSITY(Q),
1180 IF (Q<NUM) THEN
1181 Y=Y+1
1182 CONTINUE
1183 777 CONTINUE
1184 C
1185 NUM=LASTN-1
1186 ALL=Y
1187 P=ALL
1188 DO 333 Q = 1, ALL
1189 VELOCITY2(P) = VELOCITY(Q)
1190 INTENSITY2(P) = INTENSITY(Q)
1191 P=P-1
1192 333 CONTINUE
1193 C

C the following lines match up the highest and the lowest velocity bins and make sure they are within half the value of the bin size of each other i.e. 440 km/s in the model and 442 km/s in the data are considered the same bin since
C the bin values will most likely never be the exact same.

MODLOW = RVELG2(1)
MODHIGH = RVELG2(NUM)
DIFF = DVEL
DO 111 Q = 1, ALL
    DIFF = MODLOW - VELOCITY2(Q)
    Z = Q
    IF (ABS(DIFF) .LT. DVEL/2) GOTO 112
111 CONTINUE
DO 112 Q = 1, ALL
    DIFF = MODHIGH - VELOCITY2(Q)
    L = Q
    IF (ABS(DIFF) .LT. DVEL/2) GOTO 114
112 CONTINUE
114 RMS1 = 0
C
these next lines take the intensity differences
for each velocity bin

DO 654 T = 1, ALL
    IF ((T .LT. Z) .OR. (T .GT. L)) INT = 0.0
    IF ((T .LE. Z) .AND. (T .GE. L)) INT = RINOBSE2(T-Z+1)
    RMS(T) = ((INT) - INTENSITY2(T))*((INT) - INTENSITY2(T))
    RMS1 = RMS1 + RMS(T)
654 CONTINUE
PRINT*, RMS1
STD = SQRT(RMS1/(ALL)) ! the whole velocity range
PRINT*, STD
C686 CONTINUE
PRINT*, 'input the CLASS RMS value for this pointing'
PRINT*, 'type 0 if the value is unknown'
READ*, CLARMS
PRINT*, 'input the lowest velocity which contains 2useful data for your current pointing'
READ*, LOWV
PRINT*, 'input the highest velocity which contains 2useful data for your current pointing'
READ*, HIGHV
C
RMS1 = 0 ! makes sure that the input vel. range matches the
DO 211 Q = 1, ALL ! closest velocity bins in both the model
    DIFF = LOWV - VELOCITY2(Q) ! and the data it is
    C = Q
    IF (ABS(DIFF) .LT. DVEL/2) GOTO 212
211 CONTINUE
DO 212 YLOW = VELOCITY2(C)
    DIFF = HIGHV - VELOCITY2(Q)
    D = Q
    IF (ABS(DIFF) .LT. DVEL/2) GOTO 214
212 CONTINUE
214 YHIGH = VELOCITY2(D)
NUMBER = D-C+1
PRINT*, 'Q V INTDATA INTMOD RMS'
1255 TOTINT=0
1256 DO 353 Q=C,D
1257 PRINT*, Q, ' ', VELOCITY2(Q), INTENSITY2(Q), RINOBSG3(Q),
1258 2RMS(Q)
1259 RMS1= RMS1+RMS(Q)
1260 TOTINT = TOTINT + (ABS(INTENSITY2(Q)*10.4))
1261 CONTINUE
1262 PRINT*, TOTINT
1263 STD= SQRT(RMS1/(NUMBER))
1264 PRINT*, 'the average uncertainty, sigma = ',STD
1265 C
1266 C this next line calculates the goodness of fit parameter
1267 C
1268 C GOOD = ((STD-CLARMS)*(YHIGH-YLOW+10.4))/TOTINT
1269 PRINT*, 'the "Goodness" parameter, where 0 is best = ',
1270 2GOOD
1271 PRINT*, ' type y to plot a graph of the model and the data,
1272 type anything else to escape'
1273 READ*, VALUE
1274 IF (VALUE .EQ. 'Y' .OR. VALUE .EQ. 'y') GOTO 454
1275 GOTO 464
1277 CALL GRAPH2 (ALL, VELOCITY2, RINOBSG3, INTENSITY2)
1278 454 RETURN
1279 END
1280 C
1281 C
1282 C---------------------------------------------------------------
1283 C
1284 SUBROUTINE GRAPH2 (ALL, VELOCITY2, RINOBSG3, INTENSITY2)
1285 C
1286 C This subroutine plots the actual pointing data and the model
1287 C together using pgplot.A 3rd data set can also be added whether
1288 C it be actual data or another model provided the file is set up
1289 C in the same form as before
1290 C
1291 INTEGER RED, GREEN, BLACK, WHITE, CYAN, BLUE
1292 PARAMETER (RED=2) !sets up the colours
1293 PARAMETER (GREEN=3) !see comments in
1294 PARAMETER (BLACK=1) !CLOUDPIC subroutine
1295 PARAMETER (WHITE=4)
1296 PARAMETER (CYAN=5)
1297 PARAMETER (BLUE=6)
1298 C
1299 C
1300 REAL VELOCITY2 (500), RINOBSG3 (500)
1301 REAL INTENSITY2 (500)
1302 REAL VELEXTRA(500), INTEXTRA(500), IGNOREEXTRA(500)
1303 REAL VELEXTRA2(500), INTEXTRA2(500)
1304 CHARACTER*20 DATA2
1305 CHARACTER YES
1306 LOGICAL MORE
1307 C
1308 MORE=.FALSE.
1309 PRINT*, 'ADD ANOTHER DATA SET?'
1310 READ*, YES
1311 IF (YES .EQ. 'y') MORE=.TRUE.
IF (MORE) THEN
GOTO 867
ELSE
GOTO 879
END IF
867 PRINT*, 'type in the file name'
READ*, DATA2
OPEN (UNIT=02, FILE= DATA2)
C
O=0
DO 877 Z=1,500
   READ (02,*), END=881) VELEXTRA(Z), INTEXTRA(Z),
   2IGNOREEXTRA(Z)
   O=O+1
877 CONTINUE
C
N=1
DO 644 T=1,ALL
   COND = ABS(VELOCITY2(T) - VELEXTRA(N))
   IF (COND .GE. 5) THEN
      VELEXTRA2(T) = VELOCITY2(T)
      INTEXTRA2(T) = 0
      GOTO 644
   ELSE
      VELEXTRA2(T) = VELOCITY2(T)
      INTEXTRA2(T) = INTEXTRA(N)
      N=N+1
   END IF
644 CONTINUE
C
879 CONTINUE
C
call pgbeg (0,'?';1,1)
CALL PGSCI(BLACK)
CALL PGPAGE
! These 5 lines
CALL PGVSIZ (1.5, 6.5, 1.5, 3.75) ! set up the graph
CALL PGSWIN (300.,1200.,-0.02,0.18) ! window (axes, etc..)
CALL PGBOX ('BCNST', 0.0, 0, 'BCNST', 0.0, 0) ! and the
CALL pglab (' Velocity (km/s)', ' T main beam (K)'), '
CALL pglab ('model
pointing data
! These 5 lines
DO 868 Q = 1, ALL
CALL PGSCI(RED)
CALL PGSLW (3)
Call pgbin (125,VELOCITY2,RINOBSG3,1) ! model
868 CONTINUE
DO 869 Q = 1, ALL
CALL PGSCI(BLACK)
CALL PGSLW (1)
Call pgbin (125,VELOCITY2,INTENSITY2,1) ! pointing data
869 CONTINUE
IF (MORE) THEN
DO 889 Q = 1, ALL
CALL PGSCI(GREEN)
CALL PGSLW (3)
Call pgbin (125,VELEXTRA2,INTEXTRA2,1)
REAL FUNCTION FUNCTION1(RADIUS, RO)
C intensity profile for an exponential disc
FUNCTION1 = 1 * (EXP (RADIUS/RO))
RETURN
END

REAL FUNCTION FUNCTION2 (FWHM, RADIUS)
C intensity profile for a Gaussian disk
REAL FUNCTION2D, FUNCTION2E
FUNCTION2D = 1 ! (1/(2.50662827463 * ABS(FWHM/2.354)))
FUNCTION2E = (EXP(-.5*((RADIUS/(FWHM/2.354))))
FUNCTION2 = FUNCTION2D * FUNCTION2E
RETURN
END

REAL FUNCTION FUNCTION3 (RING, CONV, RADIUS)
C intensity profile for a flat ring
REAL RINGCU
RINGCU = RING/CONV
IF (RADIUS .LE. RINGCU) THEN
FUNCTION3 = 0
ELSE
FUNCTION3 = 1
END IF
RETURN
END
REAL FUNCTION FUNCTION4 (FWHM, RADIUS, GRR)

REAL FUNCTION4D, FUNCTION4E

FUNCTION4D = 1  ! (1/(2.50662827463 * ABS(FWHM/2.354)))
FUNCTION4E = (EXP(-.5*((RADIUS - GRR)/(FWHM/2.354))^2 ( (RADIUS - GRR)/(FWHM/2.354)))))
FUNCTION4 = FUNCTION4D*FUNCTION4E
RETURN
END

REAL FUNCTION FUNCTION5 (RADIUS, TRUNC, GRR, FWHM)

REAL FUNCTION5D, FUNCTION5E

IF (RADIUS .LE. TRUNC) THEN
FUNCTION5 = 0
ELSE
FUNCTION5D = 1  ! (1/(2.50662827463 * ABS(FWHM/2.354)))
FUNCTION5E = (EXP(-.5*((RADIUS - GRR)/(FWHM/2.354))^2 ( (RADIUS - GRR)/(FWHM/2.354)))))
FUNCTION5 = FUNCTION5D*FUNCTION5E
END IF
RETURN
END

SUBROUTINE CLOUDPIC(NCLOUD, CLSIZE, RINTCL, RCLOUD, 2AZCLOUD)

INTEGER RED, GREEN, BLACK, WHITE, CYAN, BLUE
PARAMETER (RED=2)
PARAMETER (GREEN=3)
PARAMETER (BLACK=1)
PARAMETER (WHITE=4)
PARAMETER (CYAN=5)
PARAMETER (BLUE=6)
INTEGER B
REAL XCIR, YCIR, RCIR
REAL RCLOUD(10,3), AZCLOUD(10,3)

This subroutine generates a picture of the physical locations of the added asymmetries using pgplot plot. The "hot" spots are drawn in red and the "cold" spots are drawn in cyan. All sizes are to scale based on the input disk size.
REAL CLSIZE(10)
REAL RINTCL(10)

CALL PGBEG(0,'?',1,1)

C these lines set up the plot window. Their function is the
C same as that stated in the graphing subroutines, although
C their values may differ.

CALL PGPAGE
CALL PGVSIZ (1.6, 9.1, 0.1, 7.6)
CALL PGSWIN (0.,200.,0.,200.)
CALL PGBOX ('BCNT', 0.0, 0, 'BCNST', 0.0, 0)
CALL PGLAB('(X)', 'clouds in a galaxy far far away',
2'clouds in a galaxy far far away')

C call pgsfs (2)
call pgsci (black)
call pgcirc (100.0,100.0, 100.0) ! sets up the whole disk

C call pgsci (green)
call pgcirc (100.0, 100.0, 37.5) ! plots a ring
call pgcirc (100.0, 100.0, 62.5) ! plots a ring
call pgsci (black)
call pgsci (black)
DO 1262 B=l,NCLoud
RCIR = 0.5*CLSIZE(B) ! gives the cloud radius to be plotted
IF (RINTCL (B) .LT. 1) call pgsci (cyan) ! for holes
IF (RINTCL (B) .GE. 1) call pgsci (red) ! for clouds

C These next lines gives x and y coordinates for the center of
C the circle
XCIR = abs(RCLOUD(B,1)*100*COS((AZCLOUD(B,1)/ISO)*
23.14159265359))
YCIR = abs(RCLOUD(B,1)*100*SIN((AZCLOUD(B,1)/ISO)•
23.14159265359))

C These lines make sure the circles are drawn on the right
C side of the disk.

IF (AZCLOUD(B,1) .LE. 180) YCIR2 = YCIR+100
IF (AZCLOUD(B,1) .GT. 180) YCIR2 = 100-YCIR
IF (AZCLOUD(B,1) .LE. 90) XCIR2 = 100-XCIR
IF (AZCLOUD(B,1) .GT. 90 .AND. AZCLOUD(B,1) .LE. 270)
2XCIR2 = XCIR+100
IF (AZCLOUD(B,1) .GT. 270) XCIR2 = 100-XCIR
call pgcirc (XCIR2, YCIR2, RCIR) ! plots the cloud or hole
DO 1262 CONTINUE
CALL PGENd
RETURN
END

C--------------------------------------------------------------
C
REAL FUNCTION GAUSSDEV (VD, SEEd1, SEEd2) ! Box-Mueller
C This function generates Gaussian deviates based on the Box-Mueller algorithm found in Bevington and Robinson (1992), Data Reduction and Error Analysis for the Physical Sciences, 2nd Edition.

C The deviates are used in this work to simulate velocity dispersion GAUSSDEV is multiplied by the velocity dispersion average value at a given radius and is then added to the velocity given by the rotation curve. Naturally, The final velocity dispersion value can be positive or negative.

REAL RGD, FGD, z1GD, z2GD, SEED1, SEED2
REAL X1RanGauss, X2RanGauss

C IF (VD) THEN
GOTO 911
ELSE
GAUSSDEV = 0
GOTO 912
END IF

911 RANDOM1=RAN(SEED1)
RANDOM2=RAN(SEED2)
z1GD = -1 + 2*RANDOM1
z2GD = -1 + 2*RANDOM2
RGD = z1GD*z1GD + z2GD*z2GD
if (RGD .GE. 1) goto 911
FGD = SQRT(-2*Alog(RGD)/RGD)
X1RanGauss = z1GD*FGD
X2RanGauss = z2GD*FGD
GAUSSDEV = X1RanGauss
912 Return
END
Appendix B

COSPEC and its Use for Work on NGC 5866

The basic COSPEC model simulates an inclined, infinitely thin disk with a given intensity profile distribution. The intensity given by a certain model can be convolved with an approximation to a telescope power pattern and a velocity spectrum is output. Several features can be added to any model in order to synthesize complicated features often seen in extra galactic observations. Such features include the addition of brighter or fainter regions sections to the chosen radial intensity profile and the addition of velocity dispersion in order to simulate more realistic physical conditions. By experimenting with the various parameters, solid conclusions about the nature and morphology of the molecular gas in a galaxy can be made.

B.1 An Overview of COSPEC

The COSPEC program was originally written to simulate a single JCMT observation of the edge-on lenticular galaxy, NGC 4710 located in the Virgo galaxy cluster. The program was extensively changed in order to simulate a disk or ring with various
intensity profiles and viewed with a representation of the IRAM 30m radio telescope for work on NGC 5866. Other features were also added to make the program more general for future use in synthesizing spectra from any galaxy in general. These changes include: a multi CO transition power pattern which can view the inclined disk anywhere along the major axis, a variable disk diameter, a user defined, 2 regime solid body rotation curve, a variable normalization area and the addition of a velocity dispersion component.

The program was designed to simulate the spectra taken by the IRAM 30m telescope by binning the “signal” collected by the power pattern subroutine while “observing” the rotating disk. The output is a spectrum, normalized to the data and binned to the same resolution as the actual data. The quality of the model is checked by comparing the simulated spectrum and the actual data on a bin by bin basis. COSPEC assumes that all of the intensity is seen by the power pattern (i.e. the specified intensity is not "radiated" isotropically). This also includes any asymmetries added to a profile. No "shadowing" is assumed so all clouds are seen regardless of geometrical location in the disk or disk inclination.

**B.1.1 The Parameters**

COSPEC has been designed to provide the user as many parameters as possible. At run time a list is presented of all the parameters and their standard values. The user is free to accept or change any number of these, any number of times, before continuing. A list of parameters and their function is presented in table B.1. Generally, the parameters control: The rotation curve (two regimes of solid body rotation, each one either rising or
falling), the intensity distribution (constant intensity disk or ring, Gaussian disk or ring, exponential disk or truncated Gaussian ring), the CO rotational transition as seen by the convolving beam ($^{12}\text{CO }J=2-1$, or $^{12}\text{CO }J=1-0$), the inclusion of asymmetries in the intensity distribution (called “clouds” in this appendix, although they can be of higher or lower intensity than their surroundings), the disk size in arcseconds, the location of the power pattern centre with respect to the centre of the major axis of the disk, and the systemic and rotational speeds. The only parameter which would need to be changed in the source code itself is the velocity dispersion relation with respect to radius (line 649). The velocity dispersion function (GAUSSDEV), which actually generates the velocity dispersion values, is independent of the radial relation and so needs not be changed. Figure B.1 shows an example of the standard parameter set as it appears at run time. The reason for the warning about changing ARCDISC first is that the conversion factor (CONV) translates all arcsecond inputs into computer units (cu). The cu is the computer distance unit. All parameters of extension, distance or location which are entered in arcseconds are converted by the code to cus internally.
THE STANDARD PARAMETER SET

a) MODEL = CONSTANT INTENSITY DISK
b) CLOUDS? = NO
c) TIP = 90.0000 degrees The inclination on the sky
d) TOP = 0. degrees The angle with respect to the power pattern axis
e) ARCDISC = 60.0000 " The disk diameter
f) VELOBJ = 745.000 km/s The systemic velocity
g) VELCON = 305.000 km/s The disk edge rotational velocity
h) TURNRAD = 10.0000 " Regime change radius in the rotation curve
i) TURNVEL = 200.000 km/s Regime change velocity in the rotation curve
j) POWER PATTERN ON? = YES
k) OFFSET = 0. " Power pattern offset. If no PP, this is ignored
l) CO transition : J=1-0
m) DVEL = 10.40000 km/s the spectrum bin size
n) VELOCITY DISPERSION ON? = NO
o) AREA USED FOR NORMALIZATION = 22.1000 T km/s
p) DISPLAY ROTATION CURVE DATA? = NO

You have made 0 changes to the parameter set

****************************************************************************
* IF THIS IS FINE, TYPE LOWER CASE "y", IF NOT, INPUT THE *
* LOWER CASE LETTER NEXT TO THE QUANTITY YOU WANT TO CHANGE *
* ---> WARNING: If changing ARCDISC, do so first <--- *
****************************************************************************

Figure B.1 An example of the prompt screen which appears at run time. Any of the standard parameters can be changed in the source code to appear as desired at run time or any change can be made from this screen.
Table B.1 The COSPEC standard parameters and their functions.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARCDISC</td>
<td>disk diameter (&quot;)</td>
</tr>
<tr>
<td>TIP</td>
<td>90 degrees for an edge-on disk</td>
</tr>
<tr>
<td>TOP</td>
<td>angle of the power pattern center to the disk major axis</td>
</tr>
<tr>
<td>CLOUDS</td>
<td>including clouds or not, logical variable</td>
</tr>
<tr>
<td>N CLOUD</td>
<td>number of asymmetries to be placed in the intensity profile</td>
</tr>
<tr>
<td>BEAM</td>
<td>power pattern on or off, logical variable</td>
</tr>
<tr>
<td>OFFSET</td>
<td>power pattern offset from the centre disk major axis (&quot;)</td>
</tr>
<tr>
<td>TRANS21</td>
<td>transition, J=2-1 default, logical variable</td>
</tr>
<tr>
<td>VELCON</td>
<td>rotational velocity at disk edge (km/s)</td>
</tr>
<tr>
<td>VELOBJ</td>
<td>systemic velocity (km/s)</td>
</tr>
<tr>
<td>TURNVEL</td>
<td>the kink velocity in the rotation curve (km/s)</td>
</tr>
<tr>
<td>TURNRAD</td>
<td>the kink radius in the rotation curve (&quot;)</td>
</tr>
<tr>
<td>DISK</td>
<td>disk model, yes or no? logical variable</td>
</tr>
<tr>
<td>RING</td>
<td>ring model, yes or no? logical variable</td>
</tr>
<tr>
<td>DISKMOD</td>
<td>what kind of disk intensity distribution? constant, Gaussian or exponential</td>
</tr>
<tr>
<td>RINGMOD</td>
<td>what kind of ring intensity distribution? constant, Gaussian or truncated Gaussian</td>
</tr>
<tr>
<td>FWHM</td>
<td>FWHM expressed as a fraction of the disk size</td>
</tr>
<tr>
<td>GRR</td>
<td>Gaussian ring radius (&quot;)</td>
</tr>
<tr>
<td>DS</td>
<td>scale length of exponential disk brightness expressed as a fraction of the radius</td>
</tr>
<tr>
<td>RING</td>
<td>ring radius, constant intensity (&quot;)</td>
</tr>
<tr>
<td>TRUNC</td>
<td>inner radius where Gaussian is truncated (&quot;)</td>
</tr>
<tr>
<td>VD</td>
<td>velocity dispersion, yes or no? logical variable</td>
</tr>
<tr>
<td>NORM</td>
<td>area used to normalize the models (T km/s)</td>
</tr>
<tr>
<td>DVEL</td>
<td>spectrum bin width (km/s)</td>
</tr>
</tbody>
</table>

B.2 How the Code Operates

The following discussion preserves the names and format of the source code when discussing specific features and formulae. Once the parameter set has been initialized (rotation curve, profile, etc...) the code works by relating velocity to radius via the specified rotation curve and intensity to radius via the radial intensity distribution. There
is now a link between velocity and intensity. The code divides up the disk into a series of
annuli and cuts each annulus into 3600 angular pieces, referred to in this work as a "unit
area". Each unit area's intensity value is placed into the appropriate velocity bin based on
the rotational velocity of the current annulus (given by the rotation curve), the unit area's
azimuthal angle and the disk inclination. Figure B.2 illustrates this.

![Diagram of COSPEC spectrum build process]

**Figure B.2** This shows how COSPEC builds a spectrum. The program takes the
intensity of each unit area and places it in the appropriate velocity bin based on the
observed velocity of the unit area. The intensity of the unit area is given by the radial
intensity distribution and weighted by the actual area of the unit area.
First, the code zeros an array which is used to store the intensities per velocity bin
(RINOBS(I)). The velocity bin width is then stated in the code (10.4 km/s in this case).
The velocity bin width is multiplied by 200 (arbitrarily, simply a reference point) and this
value is subtracted from the systemic velocity to give a reference velocity value denoted
RVEL1. RVEL1 is not the actual velocity of the first intensity but simply a reference
from which the actual useful velocities are measured. Next, the program specifies the
outer radius of the disk as 100 cu (ROUTER). The sine of the inclination angle is set so
to correct the velocities with respect to inclination. RIO is the intensity per unit area at
the centre of the disk and is the reference by which all intensities are scaled whether it is
due to the intensity distribution with radius, cloud intensity or normalization and is set to
1. The disk is broken up into several annuli which correspond to rings of equal velocity
with respect to radius. The number of annuli used is a function of the maximum
rotational velocity and the bin size of the spectra so that each annulus contains half a bin
width of velocity so as not to undersample the disk. The increments of radius, DR, are
consequently set by this procedure. Each annuli is observed over angular increments of
0.1 degree, expressed in radians, creating the unit area.

Lines 619 through 887 are the workhorse of the program. First the radius is specified by
starting at one half the radius increment, DR (i.e. the middle of the first annulus) and the
velocity is calculated from the rotation curve which was specified at run time. One the
radius and velocity have been chosen the intensity at the given radius must be found by
multiplying RIO by a specific function listed as FUNCTIONS1-5. Table B.2 lists the
functions and their associated radial intensity distributions.
Table B.2 The radial intensity distributions used by COSPEC.

<table>
<thead>
<tr>
<th>Function name</th>
<th>Radial Intensity Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUNCTION1</td>
<td>Exponential disk profile</td>
</tr>
<tr>
<td>FUNCTION2</td>
<td>Gaussian disk profile</td>
</tr>
<tr>
<td>FUNCTION3</td>
<td>Constant intensity ring profile</td>
</tr>
<tr>
<td>FUNCTION4</td>
<td>Gaussian ring profile</td>
</tr>
<tr>
<td>FUNCTION5</td>
<td>Truncated Gaussian ring profile</td>
</tr>
</tbody>
</table>

These functions specify the radial intensity distribution in the disk. No function is needed if the intensity profile is that of a constant intensity disk. FUNCTION 1 returns a value based on the radius and the scale length when an exponential disk is chosen by scaling the intensity by $\exp(\text{RADIUS}/\text{R0})$ where RADIUS is the current radial position and R0 is the scale length expressed in computer units (R0 = -DS*100cu, as found in the code). If a Gaussian disk is the chosen profile the value returned depends on the specified FWHM and the current radius. FUNCTION2 is the standard Gaussian shape:

$$FUNCTION2 = \exp\left(-\frac{1}{2} (\text{RADIUS}/(\text{FWHM} / 2.354))^2\right) \quad (B.1)$$

FUNCTION 3 is used for a constant intensity ring and makes the intensity 0 at all radii inside a specified ring radius. FUNCTION 4 is used in the case of a Gaussian ring. Here a ring radius, GRR, is specified which corresponds to the peak of a Gaussian distribution and falls off as dictated by the input FWHM.

$$FUNCTION4 = \exp\left(-\frac{1}{2} ((\text{RADIUS} - \text{GRR})/(\text{FWHM} / 2.354))^2\right) \quad (B.2)$$

Finally, FUNCTION 5 returns values for a truncated Gaussian disk. This ring is set up the same as FUNCTION4 but in this case a second radius is entered at run time for which
all intensity inside equals 0. Figures B.3-B.8 show the various how the various intensity
distributions appear in velocity space.

Before the unit area's intensity value is placed in the bin the program first corrects its
value based on its projected distance from the power pattern centre. The intensity is then
binned accordingly and the program moves on to the next unit area and next annulus and
so on. Next the program files through all velocity bins with data in them and calculates a
total area under the spectrum, BINAREA. This area is normalized to specified area
(NORM) and a normalizing factor is displayed on the screen (QWERTY). Lastly, the
binned signal can be plotted to the same scale as the observations using PGPLOT. The
spectrum is considered a good fit to the data when the sum of the difference between the
simulated spectrum and the observed spectrum squared is close to zero.

B.3 Specific Features: Problems and Testing

The following section deals with the specific features of the code and how they are used.

B 3.1 The Clouds

Asymmetries, or "clouds", can be placed in the intensity profile by making a section of
any given diameter more or less bright than the surrounding area. This feature of the
code allows the user to synthesize complex structure in the observed spectrum by placing
clouds in the appropriate geometrical place. At run time the program prompt the user for
a choice on including clouds or not. Each cloud is specified by its: radial distance from
the centre of the disk, azimuth, intensity as a multiple of the standard reference intensity,
and its diameter. No clouds may overlap in azimuth and radius, without crashing the code. To ensure that no clouds are overlapping when setting up the parameter set, a figure can be created with the circular clouds plotted on it to check for any overlap before continuing, similar to that shown in figure 3.1. Once the clouds have been characterized, the program finds the cloud centre and calculates the radial extend of the edges from the radial position and the diameter. Now that the program knows which annuli the clouds lie in it must find out at which angles the clouds encompass in order to adjust the intensity in the right velocity space. This is done by finding the edges in the azimuthal direction once an annulus has been identified as having part of a cloud somewhere in it. The program can deal with clouds which overlap azimuth = 0 and 360 but no cloud may be placed in the centre (i.e. encompassing AZ = 0 through 360 degrees), as the program does not recognize a negative radial distance. The program has located each cloud with respect to radius and azimuthal angle so when running through each annulus the intensity value changes accordingly when a section of cloud in an annulus is reached.

The code was tested to ensure the cloud portions were working correctly. When the program located a section of cloud inside an annulus it was instructed to return the edge azimuth and the radial position along with the base length (LBASE) and the cloud height (CLH). These values can easily be checked to ensure they are correct for a cloud of given size and position. The intensity of each cloud was checked by printing the intensity versus the radial extent without the effects of the power pattern or normalization on a constant intensity disk. When a section of annulus with a piece of cloud in was encountered, the intensity changed by the specified factor. Finally, the simulated spectra
bins were checked to ensure that the proper bins were receiving the proper change in intensity. This was done by comparing the spectrum of a non-normalized model, bin by bin, against the same model containing a cloud at a specified location.

B 3.2 The Rotation curve

The rotation curve can contain up to 2 solid body regimes. Either solid body regime may rise or fall with their own independent slope. The "kink" velocity and radius (TURNVEL and TURNRAD, respectively) are specified when defining the parameter set. Currently the rotation curve is designed to give negative velocities with positive radius. The direction of rotation is only important when adding asymmetries to the intensity profile so that the synthesized spectra gets changed in the appropriate velocity bins.

Testing the code is facilitated by the fact that the rotation curve should affect the synthesized spectrum in specific ways. An obvious test is to make sure that the simulated line width is 2 times the maximum rotational velocity. The term “line width” is defined here as the range of velocity space which has clear signal. Another simple check is to see where the data end up if there is no rotation. Naturally the bin which contains the systemic velocity should be the only non zero intensity. Also, when dealing with a kink in the curve, the spectra should exhibit “horns” at the bins where the velocity changes regimes, as the intensity is now distributed differently in velocity space.
B 3.3 The Intensity Distributions

COSPEC allows the user a choice of 6 radial intensity distributions throughout the disk (a ring is considered to be a special case of a disk). These include a constant intensity disk or ring, an exponential disk, a Gaussian disk or ring and a Gaussian ring in which the central hole has zero intensity. The distributions are easily checked by plotting intensity versus radius. The distributions all affect the output spectra in various ways. Plotting the spectra with the power pattern off, and with a single regime, solid body rotation curve to keep the spectra simple, differences can be seen. A flat distribution gives a spectrum that is greatest at the centre bin and drops off after that, shown in figure B.3. This is consistent with looking through less and less of a solid disk as the radius increases.

Simulated CO Spectra

![Simulated CO Spectra](image)

**Figure B.3** A constant intensity disk model spectra with no power pattern. The maximum rotational velocity is 305 kms\(^{-1}\), here and in the next 5 figures. Velocity is in kms\(^{-1}\) here and in the next 5 figures.
The exponential disk simulated spectrum looks similar but drops off much quicker as one is not only looking through less disk, the intensity is also weaker at larger radii. This is shown in figure B.4. A similar spectrum is generated with a Gaussian disk distribution, shown in figure B.5.

Figure B.4 The exponential disk intensity profile spectrum. The scale length was arbitrarily chosen as 22.5".
Figure B.5 The Gaussian disk intensity profile spectrum. The FWHM was arbitrarily chosen as 30".

Rings produce slightly more complicated spectra. For a large constant intensity ring, the maximum intensity appears in velocity bins further from the systemic velocity. When the hole is small, the spectrum produced looks similar to the flat disk model with less power. Figure B.6 shows the constant intensity ring.
A Gaussian ring looks similar to the flat ring with less power at the high and low velocity ends and more in the mid velocity range as the hole intensity is not zero but dictated by the centre of the ring radius and the FWHM of the Gaussian. This is shown in Figure B.7. Finally, a truncated Gaussian looks the same as the Gaussian ring with less power around the systemic velocity as in this case the intensity is indeed zero in the centre, shown in Figure B.8.

**Figure B.6** The constant intensity ring spectrum. The radius is 15".
Figure B.7  The Gaussian ring spectrum. The radius is 15" and the FWHM is 15".

Figure B.8  The truncated Gaussian ring spectrum. The Gaussian peak radius is 15" and the FWHM is 15" and the truncated radius is 10".
B 3.4 Normalization

In the case of the work on NGC 5866, the simulated data are normalized to the 0,0 offset pointing data. The reduced zero offset data spectrum is integrated in order to get the area under the line. The program integrates the un-normalized synthetic spectrum and then divides by the specified area. The resulting ratio is displayed on the screen and is synthesizing the pointing from which the normalizing area was taken from. Naturally, there is a danger here since the ratio returned by the program is only useful when the user is simulating the pointing used for normalizing. Other pointing simulations produce useless ratios and so, the original normalization factor for that model should be entered when the program prompts the user for the value. This means that when running the same model for multiple pointings, the pointing data which were used for the normalizing area, NORM, must be simulated first in order to get a meaningful normalization factor for use on the other pointings. The normalization factor can be checked by running the same model with no normalization and multiplying the area under the area under the simulated line by the previously found normalizing factor. The result will be the same as the area under the observed spectrum.

B 3.5 The IRAM 30m Power Pattern Approximation

This work uses an approximation of the IRAM 30m telescope power pattern presented in Greve, Kramer & Wild (1998). Those authors used scans of the new and full moon to derive the parameters for the power pattern empirically. Scans were done for wavelengths between 0.8-3 mm, which encompass the $^{12}$CO J=2-1 and $^{12}$CO J=1-0 transitions. The work was done in late 1997, roughly a year prior to the NGC 5866
observations but after adjustments to the telescope surface which were made in July of 1997.

Greve, Kramer & Wild (1998) give the degraded power pattern as a Gaussian with corrections for the error beams written as:

\[
F(\theta) = \exp[-(\sigma_r)^2] A_r(\theta) + \sum_i a_i \exp[-(\pi \theta L_i / 2\lambda)^2] \tag{B.3}
\]

where \(\sigma_r\) is the rms value of the wavefront deformation, \(A_r(\theta)\) is the Airy-type pattern (diffraction beam), \(a_i\) is the amplitude of the \(i^{th}\) error beam, \(L_i\) is the correlation length of the error distribution (for small scale random deformations in the reflector), \(\lambda\) is the wavelength and \(\theta\) is the angular distance from the centre of the power pattern. This can be simplified by ignoring the small scale RMS errors (\(\sigma_r = 0\)) and writing the diffraction beam, \(A_r\), as an approximate Gaussian:

\[
A_r = \exp(-2\sqrt{\ln 2} \theta / \theta_b) \tag{B.4}
\]

where \(\theta_b\) is the FWHM equivalent of the diffraction beam. The side lobes can be simplified by using the expression:

\[
\sum_i a_i \exp[-(\pi \theta L_i / 2\lambda)^2] = \sum_i a_i \exp[-(0.53\pi \theta / \theta_a)^2] \tag{B.5}
\]

Where the correlation length, \(L_i\), equals \(2*0.53\lambda / \theta_a\), as given by standard tolerance theory (Greve, Kramer & Wild, 1998, and references therein), and \(\theta_a\) is the FWHM equivalent of the error beam. This gives a final relationship for the telescope power pattern with respect to \(\theta\) as:

\[
F(\theta) = \exp[-(\theta / 0.60\theta_b)^2] + \sum_i a_i \exp[-(0.53\pi \theta / \theta_a)^2] \tag{B.6}
\]
where $1/(2\sqrt{\ln 2}) \approx 0.60$. The values of $\theta_b$, $a_0$, and $\theta_{\alpha i}$ are given in Greve, Kramer & Wild (1998) for the $J=2-1$ transition. The parameters for the $J=1-0$ were found by interpolating from their figure 5 data.

The power pattern subroutine works by adjusting the "observed" intensity unit area by unit area. The subroutine first translates the polar coordinates used in the spectral bin assignment part of the program to Cartesian coordinates and then gives it an XY position on the sky. The intensity of each unit is modified based on the projected distance from the power pattern centre and then rebinned in the appropriate velocity bin.

The power pattern was tested by making the model disk very small (.00001" across) to simulate a point source. The intensities were normalized to the 0,0 offset pointing and the model inclination was set to 0 (face on) so that all of the signal fell into the same velocity bin. For the $J=1-0$ transition the FWHM of the beam is 20.9". Stepping the beam across the disk produced a map of the power pattern. The same was done for the $J=2-1$ transition, FWHM of 10.5". Figure B.9 shows the approximation to the IRAM 30m power pattern from equation B.6 for the $J=1-0$ transition (as seen in lines 1098-1103 in the code) and the test results plotted on top.
Figure B.9  The solid blue line shows the approximation to the IRAM 30m telescope from equation B.6 for the J=1-0 transition. The pink squares outline the test points obtained by making the disk 0.00001 " in diameter and moving the COSPEC power pattern offset in increments of 2".

B 3.6  Plotting

Plots are generated using the PGLOT software package. The simulation is plotted as a spectrum with bins of a specified width. The velocity value of each bin is at its the centre.

When the observations and a model are plotted together the program needs to know how to match up the model and the data velocity bins since each has a slightly different velocity value. The program calls two bins the same only if the difference between the two velocity values is less than half of the bin width value. This ensures only one bin from each are considered the same and compared. This also ensures that the synthesized spectra and the data can be plotted on top of one another for visual comparison.
B.3.7 The "Goodness of Fit" parameter

The "Goodness" parameter was used as a measure of how well a particular model fit the data and is computed in the RMSCLAC subroutine. The idea is to compare bin by bin the synthesized spectra and the pointing data. The measure involves comparing the intensity value of each velocity bin from the model and the same velocity bin from the data. The differences between the intensity values for the same velocity bin are squared and the average uncertainty found (STD in the code). The average uncertainty then has the CLASS RMS value, the uncertainty associated with the observed data, subtracted from it in order to not count the intrinsic scatter in the signal and this corrected uncertainty is then multiplied by the value of the velocity range, in kms⁻¹, and divided by the total area under the data line. If the model is a perfect match then the goodness of fit parameter will return 0. To test this, real data from an actual pointing was sent through the subroutine as a substitute for model data. The Goodness parameter returned values on the order of zero to the 10th decimal place.

B.3.8 Velocity Dispersion

The average velocity dispersion value at a given radius is specified in the code (line 649). This value is sent to the GAUSSDEV function which uses it as the most probable value returned by a Gaussian random number generator (a Monte Carlo simulation based on the Box-Mueller algorithm, Bevington & Robinson, 1992). The Gaussian random number returned can either be positive or negative and is added to the velocity of the current unit area given by the rotation curve. In this fashion, the final observed velocity of any unit area can be higher or lower or the same as that given by the rotation curve and therefore
potentially placed in a different velocity bin than would have been otherwise. This feature was added in order to try and widen the simulated line width without having to raise the maximum rotation speed beyond that seen in the stars and the ionized gas.

The GAUSSDEV function was tested by running the same average velocity dispersion value (50 km s\(^{-1}\)) through the function and adding it to the same velocity that would be given by rotation (100 km s\(^{-1}\)) 5000 times. The result was a Gaussian distribution centred on 100 km s\(^{-1}\).

### B 3.9 Problems

Several limitations of the code have already been discussed. One of the problems intrinsic to the way the code works is in the binning procedure. When running a completely symmetric model where the centre velocity bin is exactly centred on the systemic velocity and the maximum and minimum velocities are evenly divisible by the bin widths, equal bin numbers away from the centre should have equal intensity values. The bin number is assigned by (line 712):

\[
 IVEL = \text{ININT} \left( \frac{\text{VTOOBS} - \text{RVEL1}}{\text{DVEL}} \right) \tag{B.7}
\]

where \( IVEL \) is the bin number, \( \text{VTOOBS} \) is the observed velocity, \( \text{RVEL1} \) is the reference velocity and \( \text{DVEL} \) is the bin width. \( \text{ININT} \) is the FORTRAN function which converts a real number into an integer. To illustrate the problem imagine the case where the central bin is bin number 139. In this case equal velocity widths away from the centre bin should have the same intensity values, that is bin number 134 and bin number 144 should have equal intensity. However if the velocity, \( \text{VTOOBS} \) is a half integer value,
i.e. 22.5 kms$^{-1}$, then the bin number is not going to be symmetric. For example:

$\text{IVEL} = \text{ININT}\left(\frac{(-22.5 - -695)}{5}\right)$, $\text{IVEL} = \text{ININT}(134.5) = \text{bin number 135}$, or in the 20 kms$^{-1}$ from the centre bin. On the other side, $\frac{(22.5 - -695)}{5} = 143.5 = \text{ININT}(143.5) = 144$, or the 25 kms$^{-1}$ from the centre bin. Fortunately this only happens when VTOOBS falls on an half value and only creates an error of $\sim 0.1\%$.

Another bug in the code is that when the value of the maximum and minimum rotation velocities are not evenly divisible by the bin width, the lowest velocity bin gets the left over intensity, making it artificially large. Fortunately that bin is usually suppressed by the power pattern produces a negligible error.

### B.4 The COSPEC Data Fitting Experiments for NGC 5866

This section is a short description of the methodology used in running the COSPEC experiments for synthesizing the spectral data from NGC 5866. The quantitative details of the bit fit results can be found in chapter 3 and details of the other experiments are presented in appendix C. The modelling philosophy was to start with the simplest model and build on the successes and failures of that until a model which most satisfactorily fit the data was found. The following outlines the successive iterations and gives a qualitative description of each.

Often it was very easy to improve the fit to only one pointing so that the model matched almost perfectly. However, using the same model but pointing the power pattern at another offset, resulted in a dramatic worsening of the model fit to the data. The goal
was to synthesize all of the pointing data with just one model. The overall "goodness of fit" for a model was judged on the basis of how well the model fit the four centremost pointings. This is somewhat subjective as averaging the goodness parameter for the 4 centremost pointings can often smear out widely varying matches for different pointing but the same model and often it was left to the eye to be the final judge. The criteria, then, is a low average goodness for the 4 centremost pointings and consistency in how well each pointing was matched with the data.

The model consisted of a 60" diameter, constant intensity disk with the observed stellar rotation curve as given by Fisher (1997) for NGC 5866. The obvious failure of this model is that the data suggest that the maximum rotational velocity is about 100 km/s higher than the observed stellar rotation curve allows. The telescope was centred at 745 km/s and the 0,0 offset spectrum data clearly show emission out to ~1100 km/s on the redshifted side and signal out to ~440 km/s on the blueshifted side. Only a higher model rotational velocity can reproduce the observed line width. This problem is seen in all of the pointings. By having a maximum rotational velocity of 200 km/s at 30" the velocity range seen by the power pattern is too narrow. This model produces Gaussian shapes for the signal at all offset and cannot make the "saw tooth" pattern seen in the data for the outer pointings (i.e. -9,7, 9,-7, and 17,-14 offsets).

Fisher (1997) also gives a rotation curve defined by the ionized gas, as delineated by the [O III] line. This rotation curve also does not extend to sufficiently high velocities to reproduce the observed CO line width. However, some improvement is achieved because
of the fact that the [O III] data show two solid body regimes. The first regime features a rapid rise in velocity up to 68 km/s at 2.49", which is followed by a more gradual rise up to 203 km/s at 30". By having larger velocities at smaller radii, this rotation curve puts a larger range of velocities inside the power pattern (at the centre pointing) compared to the stellar rotation curve, and so produces a wider spectrum. Unfortunately the [OIII]-based rotation curve only improves the model slightly; the simulated line is still too narrow by about 200 km/s. One major improvement is that the offset pointing simulations reproduce the saw tooth shape seen in the data, only at the wrong velocity positions. The overall "goodness of fit" is not much different than that of the stellar rotation curve but the fact that the [O III] rotation curve can reproduce the observed shape of the spectra suggests what the actual rotation curve for the CO might be like qualitatively.

How should the optical rotation curves be modified to provide significantly better fits to the CO data? The first step in answering this question was to try a rotation curve which rose to 300 km/s at 30". This gave the immediate improvement in that the line width could now be ~600 km/s in theory. The main problem with this model is that too much of the high velocity is not seen by the 20.9" FWHM power pattern. To reduce this problem, several rotation curves were examined with kinks at various velocities and radii, like that seen in the ionized gas rotation curve. The most successful of these curves rose to 200 km/s at 10", and then to 305 km/s at 30". This rotation curve not only reproduced the observed line widths, irrespective of radial intensity distribution, for all pointings, but also displayed the saw tooth pattern at the appropriate velocities and produced "horns" seen in the 0,0 pointing data. This provides a closer match to the centre pointing data
since they clearly show a dip in the centre. The constant intensity disk model using this rotation curve provided reasonable fits although the outer pointings has too much power.

Once a rotation curve had been found that could reasonably reproduce the observed line width, various intensity distributions were tried using the best rotation curve. COSPEC allows the user to choose between 6 different intensity distributions. Following the methodology of before, the simplest distribution was modelled first and subsequent models of greater complexity introduced when the simpler model failed.

The first intensity distribution modelled after the constant intensity disk was an exponential disk. Various scale lengths were tried in order to assess how well this distribution would work. Fractional scale lengths below $-0.5$ produce less satisfactory models than the constant intensity disk: The synthesized line widths are too narrow and integrated intensities at offset pointings are too small. Larger scale lengths ($> 0.5$) produce slightly better models than the constant intensity disk. The centre pointing remains about the same but the offsets are a little weaker and match the data better but on the whole unacceptable.

The Gaussian disk model results are comparable to the exponential disk models. This is not surprising since there is little difference in the nature of these models. Both peak at the centre and fall off at a characteristic rate defined by either the scale length for the exponential disk or the FWHM for the Gaussian disk. Small Gaussian FWHM fail to improve on the constant intensity disk model (FWHM $< 0.5$) while the larger FWHM ($>
0.5) improve the model in the same fashion as the larger scale length exponential disk. No improvement over the exponential disk is found.

After trying the various disk models the next logical choice was to try various ring models for the intensity distribution. This seemed like the logical next step since the 0,0 offset pointing shows a clear dip in intensity around the systemic velocity. This can be interpreted as a hole in the centre of the intensity profile. As before, a constant intensity distribution was chosen first. The constant intensity ring model is the same as the constant intensity disk, only with zero intensity within a given radius. Using various different hole radii none of the flat ring models proved better than any previous model. These models predict too much power in the offset pointings, and generate synthetic lines broader than observed. The centre pointing can be improved slightly however.

The Gaussian ring models worked the best. These models take power out of the centre and distribute it further out while still dropping the intensity at large radii, so that predicted integrated intensities at outer offset pointings are not unacceptably large as in the flat ring models. Several peak intensity radii and Gaussian FWHM were tried. Varying the radius and the FWHM led to either too much power in the centre and not enough at large radii or vice versa. Through trial and error a balance which produced the best results was found. This was a radius of 15" and a FWHM of 15".

The final intensity distribution tried was the truncated Gaussian ring. These models did not improve on the Gaussian ring model enough to warrant its use. The centre pointing was improved but the offsets were given too much power. Overall these models worked
as well as the Gaussian ring but not better. Arguing for simplicity the Gaussian ring was chosen over the truncated Gaussian ring as the best intensity distribution to model NGC 5866.

Naturally, all of the varying intensity distribution might be improved by fine tuning the rotation curve which was chosen using the constant intensity disk model. The major problem in synthesizing the data was reproducing the observed line width. This could only be solved through the choice of an appropriate rotation curve and not intensity distribution. For this reason and simplicity sake, the best fitting rotation curve was assumed to be independent of intensity profile.

The final stage in the modelling was to incorporate asymmetries into the Gaussian ring profile in order to further match the data. These clouds were introduced at several locations inside the disk in order to create the proper effect on the spectrum at the proper velocities. Their spatial locations in the model do no represent anything physical as there is no unique placement that will produce a unique spectrum. Broad statements such as what side of the disk they need to be placed on can be made, however. The main areas where the Gaussian ring failed are that the velocity bins around the systemic velocity in the 0,0 offset data have too much power and the redshifted side in the of the line Gaussian ring model is too weak. This was corrected by placing "hot" and "cold" clouds in the ring profile, through trial and error, until a reasonable fit was reached.
After a best fit model had been found (see table 3.3) other mechanisms were suggested to account for the large line width and often weak outer pointing with respect to the models. In order to reconcile the CO line width and the predicted line width of both the stellar and ionized gas rotation curves, velocity dispersion was added to the models which used these rotation curves. The idea was that velocity dispersion would necessarily cause some "spill over" from the highest and lowest velocity bins given by the rotation curve and widen the line. The velocity dispersion relation to radius was taken from Fisher's (1997) data and a Gaussian random number generator was used to produce velocity dispersion values. Even with velocity dispersion, these models still could not widen the synthesized line width enough to be considered satisfactory.

Since many of the models reveal simulated spectra that are too powerful at the outer pointings, a tilt between the major axis of the disk and the line of power pattern pointings was introduced (this angle is not in the plane that determines whether the disk is face on or edge on). It was hoped that a small enough angle which could be blamed on pointing error might improve the fit. Large angles (10-20°) did improve the overall fit by ~10% over the best fit model but were not considered due to the implied unphysical nature of the CO distribution in NGC 5866. This would mean that the CO is not associated with the visible dust lane and so these models were disregarded.
Appendix C

COSPEC Experiment Results

The following tables list the results of the various trial and error experiments using COSPEC as described in appendix B and chapter 3. All model with less than 4 pointings simulated were clearly not going to fit the data and so abandoned. Table C.1 lists the rotation curve experiments using a constant intensity (flat) disk. Table C.2 shows various intensity distribution experiments and table C.3 shows the unused models, which had the major axis tilted with respect to the line of power pattern pointings. Note that for the Gaussian ring models, the quoted normalization factor will no longer work in the version of COSPEC presented here. If running these models, the new normalization factor which can be founded by simulating the 0,0 pointing will still produce the same goodness of fit value.
Table C.1  Constant intensity disk model with varying rotation curves.

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Table C.2  COSPEC results for the morphology of the molecular gas in NGC 5866 using various intensity distributions. A full description of each parameter and how they were used can be found in appendix B.

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1999-2001
M.Sc. in Astronomy, October 2001, Saint Mary’s University, Halifax, NS

1994-1998
B.Sc. in Physics, minor in Philosophy, May 1998, Mount Allison University, Sackville, NB

1991-1994
High School Diploma, Honours, Moncton High School

RELEVANT EXPERIENCE:

2001
Senior lab instructor for the physics component of the Forensics program at Saint Mary’s university. This included preparing and overseeing the labs, coordinating the lab demonstrator, ensuring the safety of the students and lecturing when the course professor was absent.

2000-2001
Tutorials for the first year physics class, Saint Mary’s University. This involved preparing problems from the text book and presenting them to the students in a way that would allow them to gain a better understanding of the course material. This was a part time faculty position.

2000
Coordinated an internet based astronomy class at Saint Mary’s University along with other graduate students. Responsibilities included overseeing and marking tests and exams along with handling any problems that came up during the course because the class professor teaches at the University of Hawaii.
1999-2001
Telescope tour guide for the public at the Burke-Gaffney Observatory, Saint Mary's University.

First year physics lab demonstrator, Saint Mary's University.

Canadian Astronomical Society (CASCA) graduate student representative for Saint Mary's University.

1998-1999
Research assistant for Dr. Bob Hawkes at Mount Allison University. Responsibilities included equipment preparation, data reduction and analysis.

Junior Physics lab technician. Responsibilities include setting up labs, coordinating lab demonstrators and ensuring that the labs are run smoothly and safely.

1998
Prepared and delivered several first year Astronomy lectures at Mount Allison University.

Researcher at Bubble Technology Industries, Chalk River, ON. This position was funded through the Deep River Science Academy and involved taking on 2 honours high school students to supervise and grade in the research for 6 weeks in order to give them a better understanding of what “science in the real world” is like. The students prepared a report, a presentation for professional research scientists and a poster presentation for the general public. The students received Ontario high school credits in a co-op program.

1995-1998
Physics lab demonstrator at Mount Allison University. Several classes were covered including: first year physics, 3rd year biophysics and introductory Astronomy.

PUBLICATIONS:

Full Refereed Journal Articles


**Internal Publications and Conference Proceedings**


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