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MOLECULAR GAS IN SEYFERT GALAXIES

by

Padeli Peter Papadopoulos

A Thesis submitted in conformity with the requirements
for the Degree of Doctor of Philosophy in the
University of Toronto

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Δως μοι πα στω και την γαιαν κινησω.

(Αρχιμήδης)
This work would not have even started, let alone been completed if it wasn’t for the tireless support given to me from a multitude of people. Albert Einstein once expressed his deep acknowledgment towards his predecessors by saying that he saw further because he was standing on the shoulders of giants. I can say similarly that if I entered the world of Exploration and its accompanying adventures, if I was allowed to immerse myself into the Mysteries of the Cosmos and left to wonder in its Shores, it was because I was also standing in the shoulders of giants, my parents Katerina and Christos.

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Abstract

Molecular gas in Seyfert Galaxies

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In this work we examine the physical conditions of the global molecular gas reservoir in the host galaxies of Seyfert nuclei. The prime motivation is to examine if there are any large scale differences among the two types of Seyferts and whether the observed larger star formation rate in the host galaxies of type 2 Seyferts is also accompanied by a systematically larger molecular gas reservoir. Since starburst activity is expected to influence the state of the molecular gas and hence have an effect on outcome of the different methods used to derive its mass, we also conducted a multi-transition study of the inner starburst region of the archetypal Seyfert 2 galaxy NGC 1068.

For the statistical part of our study we acquired sensitive $^{12}$CO, $^{13}$CO, J=1–0, J=2–1 observations and collected available data from the literature for a sample of 27 Seyfert galaxies. We find that Seyferts have average $^{12}$CO/$^{13}$CO J=1–0 and J=2–1 line ratios of $\langle R_{10}\rangle=12$ and $\langle R_{21}\rangle=13$ respectively, with no discernible dependence on the Seyfert type.

The $r_{21}= (2–1)/(1–0)$ line ratio for $^{12}$CO does not reveal any significant difference between the two types but Seyferts as a class seem to have systematically lower values of $r_{21}$ ($\sim 0.5 - 0.7$) than average spirals and starbursts. Moreover for all the galaxies examined, but especially for Seyferts and starbursts, we find that $r_{21}$ is likely to be smaller as the area of the galaxy sampled by the telescope beam becomes larger. This is interpreted as the consequence of a global gas excitation gradient in galaxies where warm ($T_{\text{kin}} \geq 20$ K) gas lies confined in their central regions ($\leq 1$ kpc) while a colder
(T_{kin} \leq 10 \text{ K}), and/or sub-thermally excited gas phase dominates the more extended CO emission in the disk. For Seyferts and starbursts we find that this gas excitation gradient may be quite similar.

We also present fully sampled $^{12}\text{CO}$, $^{13}\text{CO}$ J=2–1, 3–2 maps of the inner $\sim 1' \times 1'$ region of NGC 1068 and combine these measurements with an interferometric map of $^{12}\text{CO}$ J=1–0 that includes single dish data and hence recovers all the flux present. This allows a reliable estimate of the $^{12}\text{CO}$ (J=3–2)/(J=1–0) ratio at the highest angular resolution currently possible and the use of this sensitive line ratio to probe the physical condition of the molecular gas. We also obtained interferometric maps of the $^{13}\text{CO}$, C$^{18}\text{O}$ J=1–0 and two single-dish measurements of the C$^{18}\text{O}$ J=2–1 transitions.

The observed line ratios suggest a two-component gas phase being present in the starburst region of NGC 1068. The one component is diffuse, warm (T_{kin} \geq 35 \text{ K}) and not virialized, with moderate $^{12}\text{CO}$ J=1–0 optical depths ($\tau \sim 1 - 2$) and dominates the $^{12}\text{CO}$ emission. The other component is more spatially concentrated and dense, contains the bulk of the molecular gas mass, and is very likely virialized. In this phase the rarer isotopes $^{13}\text{CO}$, C$^{18}\text{O}$ have significant optical depths ($\tau \geq 1$).

The usual way of estimating molecular gas mass is from the $^{12}\text{CO}$ J=1–0 luminosity and a standard galactic conversion factor. This may overestimate the gas mass present if the gas phase dominating the emission of $^{12}\text{CO}$ is not virialized. Hence, earlier suggestions that the larger $^{12}\text{CO}$ J=1–0 luminosity of Seyfert 2 with respect to Seyfert 1 galaxies means a correspondingly larger molecular gas mass must be viewed with caution. Indeed the reported differences in the CO luminosity between the two Seyfert types can be readily attributed to the presence of warmer and possibly non-virialized gas in type 2 more often than in type 1 rather than to a difference in total molecular gas mass.

On the other hand deducing molecular gas mass from $^{13}\text{CO}$ under the assumption that this isotope has small/moderate optical depth may significantly underestimate the gas mass present since much of this gas mass may be contained in the dense gas phase where $^{13}\text{CO}$ can have substantial optical depth.
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Chapter 1

Introduction

1.1 Seyferts and nuclear activity in Galaxies

The study of Active Galactic Nuclei (AGN) started when early (Fath 1909) spectroscopic surveys demonstrated that while most of the brightest spiral “nebulae” showed absorption spectra due to large numbers of stars, one of them, NGC 1068, had six emission lines in its spectrum. Other astronomers like Slipher (1917) and Hubble (1926) obtained much better spectra of NGC 1068, 4051 and 4151 and started noting their distinct spectroscopic characteristics. After seventeen years, Carl Seyfert (1943) studied these and other galaxies systematically and isolated the small fraction of them that exhibit broad emission lines over a wide range of ionization and originating from a small bright nucleus. This class of galaxies are known as Seyfert galaxies and they are the most numerous known type of galaxies with an AGN.

Later, after the optical identification of several of the strongest radio sources with galaxies (Baade & Minkowski 1954) or “stellar-like” objects other types of AGN were found. The discovery of radio galaxies and Quasi Stellar Objects (QSOs) was made with the later realization that they were very luminous AGN, many of them observed at very large distances. These large distances made it difficult to identify the host galaxy in many such objects. However, continuous advancements in observational techniques as well as a better understanding of the underlying physics at work made it apparent that QSOs and Seyfert galaxies are similar types of objects constituting
a continuous luminosity sequence with the Seyferts at the low luminosity and the QSOs at the high luminosity end. The power source that lies at the centers of these extraordinary objects is thought to be a super-massive black hole \((M \sim 10^6 - 10^{10} \, M_\odot)\) and its accompanying accretion disk.

The emission lines of Seyferts have been studied extensively in the optical regime and their characteristics point to two types of AGN present in Seyfert galaxies. The Seyfert 2 nuclei have both permitted lines of H I, He I and He II as well as forbidden lines like O III and N II with widths ranging from 200 to 700 km s\(^{-1}\). The Seyfert 1 nuclei include all these lines plus a set of much broader lines of H I, He II and Fe II with FWHM\(~ 3000 \, \text{km s}^{-1}\).

The source of these wide lines is thought to be gas clouds in the broad line region (BLR) that are photo-ionized by the intense UV/X-ray continuum emanating from the accretion disk. The size of this region is of the order of \(L_{\text{BLR}} \sim 0.1 - 1 \, \text{pc}\) (e.g., Peterson 1993; Robson 1996 and references therein) and the photo-ionized clouds are thought to be gravitationally bound by the central super-massive black hole. In this picture the very large widths of the lines emitted by the gas in the BLR are a direct consequence of the large virial velocities expected for gas gravitationally confined to a small volume around the super-massive black hole. The narrow line emission originates from a much larger volume with a characteristic size of \(L_{\text{NLR}} \geq 100 \, \text{pc}\) (see Robson 1996), the Narrow Line Region (NLR). This is the largest volume in galaxies that harbor AGN where the ionizing radiation from the central source still dominates over stellar sources and it is the only AGN-related component that can be spatially resolved in the optical.

A dusty molecular torus with a size of \(L \sim 1 - 10 \, \text{pc}\) (Krolik & Begelman 1986) seems to be responsible for the observed spectroscopic differences between the two types of Seyferts. In a Seyfert 2 (hereafter Sy2) this torus obscures the AGN and the BLR but not in a Seyfert 1 (hereafter Sy1). Two important observations that made the aforementioned picture more convincing were a) the detection of a “hidden” BLR in Sy2 galaxies in polarized light (Antonucci 1991 and references therein) where the broad emission lines are reflected into the line of sight by a “screen” of electrons on
top of the torus and b) the direct detection of molecular gas material on scales ≤ 200 pc of the Active nucleus in NGC 1068 (Planesas et al. 1991; Tacconi et al. 1994; Helfer & Blitz 1995) that is very likely associated with the torus. However, higher angular resolution measurements are needed to demonstrate clearly that this is indeed the case, since the interferometric measurements currently available correspond to a linear resolution of ~ 200 pc.

1.2 The Seyfert-starburst connection

An important aspect of the Seyfert phenomenon is the possible relationship between the star formation occurring in the host galaxy and the presence of the Active Galactic Nucleus (AGN) (e.g., Norman & Scoville 1988; Heckman et al. 1989; Linden et al. 1993). The cause is thought to be infalling molecular gas that acts as a “fuel” for both star formation and the AGN. However, the small size (≤ 100 pc) of the molecular torus argues against any direct dependence of its characteristics on global (L ≥ 1 kpc) properties of the host galaxy like molecular gas mass and star formation rate.

Nevertheless, Heckman et al. (1989) find that Sy2 galaxies have on average ~ 4 times higher far infrared (FIR) luminosity than Sy1 or non-Seyferts. They also find that Sy2’s have higher CO luminosity than Sy1’s or non-Seyferts when normalized to other global variables like the blue luminosity or the HI content of the host galaxy. These results imply that Sy2 galaxies have higher star formation rates and are more gas rich than Sy1’s and similar field galaxies over scales of L ≥ 1 kpc. Later studies (Maiolino et al. 1995 and Maiolino et al. 1997)) that use a larger sample do not confirm the “excess” $^{12}$CO J=1–0 luminosity of Sy2’s but they do find that Sy2’s galaxies are undergoing starbursts more often than Sy1’s. Such results cannot be easily reconciled with a small size for the AGN-obscuring torus and point towards a more complex picture where the obscuring material may be distributed on much larger scales than previously thought (Maiolino & Rieke 1995).

Many studies examining the molecular gas of starburst galaxies have shown that the gas excitation is significantly higher in the circumnuclear star-forming region than
in quiescent regions in the disk of the Galaxy (e.g., Rieke et al. 1980; Wall et al. 1993; Devereux et al. 1994; Aalto et al. 1995). This is to be expected since elevated star formation with the associated high density of O and B stars and the high supernova rate heats, disrupts and compresses molecular clouds. Therefore it is possible that the global gas excitation properties of the two Seyfert types are different, with type 2 containing on average warmer molecular gas than type 1. Furthermore, since the majority of Seyfert galaxies are of type 2 (Maiolino & Rieke 1995), a corollary is that Seyfert galaxies as a class have elevated star formation rates compared to similar field galaxies. Further evidence that starbursts may play an important role in the Seyfert phenomenon can also be found in studies of the featureless UV continuum (Heckman et al. 1995) observed in these galaxies where a circumnuclear starburst as well as the AGN (e.g., Barvainis 1993) may be contributing to the UV luminosity.

1.2.1 Molecular gas in starburst environments

The fact that the intense star-forming activity observed in a starburst is expected to strongly influence the molecular gas that fuels this activity allows the use of such environments as natural “laboratories” where the molecular gas is subjected, over large scales, to conditions not encountered in the Milky Way or the disks of quiescent spirals.

This is important since the standard factor $X = \frac{M(H_2)}{L_{CO}}$ used to convert the luminosity of $^{12}$CO J=1–0 to molecular gas mass (see Young & Scoville 1991; Bryant & Scoville 1996) depends on the ambient conditions. Initial studies of the molecular gas in starburst environments like the one in the Irr II galaxy M 82 do not readily reveal a substantial influence of the environment on the $X$ factor (Young & Scoville 1991 and references therein). However, later studies that make use of a significantly enlarged data-set of molecular lines (Wild et al. 1992) suggest that the luminosity of $^{12}$CO may not be a reliable mass tracer in the active regions of M 82. A similar picture has emerged for the nuclear region of a less intense starburst the face-on Sc galaxy IC 342 (Eckart et al. 1990).

This can complicate the estimates of molecular gas that use the $X$ factor in star-
burst environments. For these reasons, the detailed study of the gas in more energetic starbursts than the ones already studied has the potential of exploring a wider range of the parameter space of the physical conditions of the molecular gas. From this point of view studying the molecular gas in Seyfert galaxies has an importance that goes well beyond the scope of simply examining the gas content in these galaxies since some of the most powerful starbursts are found in the circumnuclear regions of Seyfert nuclei (e.g., Rieke 1991 and references therein).

1.3 Plan of the thesis

In this thesis, we will use an approach that consists of two parts, namely, a) a survey of CO line ratios in a sample of Seyferts at low angular resolution, and b) the study of an individual object at high resolution. In the survey we observed a large number of Seyferts at a resolution that samples the molecular gas on large scales (> 5 kpc) and use extensive data for other galaxies found in the literature in order to examine the global gas properties of Seyferts and compare them to other types of galaxies. This work is described in Chapters 1, 2 and 3.

The early study of the molecular gas and dust in Seyferts by Heckman et al. (1989) suggested that it is Sy2 that seem to be “standing out” with respect to Sy1 or normal spirals in terms of their $^{12}$CO $J=1-0$ and FIR luminosity. For this reason, we chose to study the molecular gas of a Sy2 galaxy in detail. The galaxy of choice is the archetypal Sy2/starburst galaxy NGC 1068. The rationale behind this particular choice and the acquired data are described in Chapter 4 and a discussion about the physical conditions of the gas revealed by these observations follows in Chapter 5. Finally in Chapter 6 we summarize our conclusions and describe future work that is important for addressing the remaining issues.
Chapter 2

The line ratio survey: Observations and Data reduction

2.1 Sample selection criteria

Our sample includes almost all (24) the Seyfert galaxies in the Heckman et al. (1989) survey that have been detected in the $^{12}\text{CO}$ J=1–0 transition plus the Sy1 galaxy Ark 564, and the LINER (previously classified as Sy2) NGC 6764 neither of which were included in the Heckman et al. sample. In the literature we found multi-transition CO data with reliable estimates of line ratios for two more Sy1 galaxies namely I Zw 1 and Mrk 817 which we include in our study. Note that these objects have been previously classified as Radio Quiet Quasars (RQQs) but several studies (Morgan & Dreiser 1983; Chini, Kreysa & Biermann 1989; Alloin et al. 1992) indicate that RQQs are simply Sy1 galaxies seen at a greater distance.

Our choice of the particular sample was dictated by the fact that, when we started our project, this was the only large sample of Seyferts that had been observed in $^{12}\text{CO}$ J=1–0. Since we thought that it was crucial that we observe transitions of the much less abundant and therefore weaker isotope $^{13}\text{CO}$, only observations of a sample of galaxies of known $^{12}\text{CO}$ luminosity could allow effective planning of our observing campaign and a realizable estimate of the necessary telescope time.
2.1.1 A Bias: the $100\mu$m flux as a selection criterion

The sample used for our line ratio survey consists of the galaxies detected in the $^{12}$CO J=1−0 survey done by Heckman et al. (1989). Among their selection criteria they employ a flux density criterion that involves the IRAS $100\mu$m flux, namely $S_{100\mu m} > 10$ Jy. This criterion introduces a bias in their sample towards type 2 Seyferts that are known to be stronger Far Infrared (FIR) emitters than type 1 (Spignolio & Malkan 1989; Maiolino et al. 1995). We tried to partly remedy this situation by including in our line ratio survey three Seyfert 1’s that had reliable $^{12}$CO data for the purpose of estimating line ratios.

Obviously a better way is to only use selection criteria that do not introduce any biases towards either type of Seyferts and use the resulting sample for a $^{12}$CO J=1−0 survey. A sample with such properties is the $12\mu$m galaxy sample defined by Spignolio & Malkan (1989) which uses the IRAS $12\mu$m flux as its criterion. At this wavelength the AGN seems to be contributing, more or less, a constant fraction of the bolometric luminosity of the host galaxy irrespective of AGN type. We conducted an extensive $^{12}$CO J=1−0 survey of this sample. Our results have been combined with the results of another survey and are presented and analyzed in Maiolino et al. (1997).

2.2 The NRAO 12m Telescope observations

We used the NRAO 12m telescope\(^1\) in two four-day observing runs starting on 1994 April 28 and 1995 April 19 to observe the $^{12}$CO J=1−0, 2−1 transitions at 115 GHz and 230 GHz respectively for all the galaxies in the sample and $^{13}$CO J=1−0 at 110 GHz in all cases where reasonably strong $^{12}$CO emission was detected. The profile of the telescope main beam is closely approximated by a gaussian with HPBW of 55" and 32" at 115 GHz and 230 GHz respectively. We monitored the focus and pointing of the telescope by frequently observing bright quasars and planets. The rms pointing error was found to be $\sim 7\"$ at both frequencies. We performed all

\(^1\)The National Radio Astronomy Observatory (NRAO) is a facility of the NSF, operated under a cooperative agreement by Associated Universities, Inc.
observations using a beam switching mode with beam throws 4' - 6' in azimuth, and at rates of 1.25–2.5 Hz. The 256 x 2 MHz filterbank was used, giving a velocity range of 1336 km s⁻¹ at 115 GHz and 668 km s⁻¹ at 230 GHz. We have converted the original temperature scale $T_A^*$ of the NRAO 12m spectra to the $T_{mb}$ scale, assuming efficiencies of $n_M^*(115 \text{ GHz})=0.80$ and $n_M^*(230 \text{ GHz})=0.48$ (Jewell 1990). The main beam brightness temperature scale $T_{mb}$ is the appropriate scale for our observations since the observed sources are not significantly larger than the HPBW of the telescope and $T_{mb}$ is appropriately normalized to the main beam solid angle $\Omega_{mb}$.

Spectral line observations of small diameter standard sources were performed with and without beam switching in order to search for any systematic effects during the nutation of the secondary. No such effects were found for the beam throws and frequencies employed during our observing runs. The rapid beam switching mode gave us remarkably flat baselines in most of our spectra. As a result only linear baselines had to be removed.

We estimated the rms error associated with each line intensity measurement using the relation

\[
\left( \frac{\delta T}{T} \right) = \left[ \left( \frac{\delta T}{T} \right)_{\text{ther}}^2 + \left( \frac{\delta T}{T} \right)_{\text{rrms}}^2 + \left( \frac{\delta T}{T} \right)_{\text{syst}}^2 \right]^{1/2}.
\]  

(2.1)

The first term in Equation 2.1 expresses the thermal rms error. If $T$ is the main beam temperature averaged over $N_{ch}$ channels and the baseline subtracted is defined more or less symmetrically around the line profile by a total number of $N_{bas}$ channels, then

\[
\left( \frac{\delta T}{T} \right)_{\text{ther}} = \frac{\delta T_{ch}}{T} \left( \frac{N_{bas} + N_{ch}}{N_{bas}N_{ch}} \right)^{1/2},
\]  

(2.2)

where $\delta T_{ch}$ is the thermal noise per channel, estimated for each individual spectrum. The second term expresses residual rms errors ($\text{rrms}$) and it is of the order of $\sim 0.10$ at 115 GHz and $\sim 0.15$ at 230 GHz, while the 3rd term is of the order of $\sim 0.10$ for both frequencies. More details about this equation and the various sources of error in millimeter spectroscopic measurements that are expressed by the two additional
terms in Equation 2.1 are contained in the Appendix, (Equation A.2). We note that in many cases in the literature only the thermal rms error is reported (i.e., the first term of Equation 2.1) which results in significant underestimates of the true error associated with mm spectral line observations.

A principal goal of this part of our study is to obtain accurate line ratios making no a priori assumptions about the beam-source coupling factor. For these reasons, in most of the objects observed with the NRAO 12m telescope, we observed the $^{12}$CO J=2–1 emission in a rectangular 9-point grid with a cell size of 15″, centered on the point of the $^{12}$CO(1–0) measurement. Then we convolved the grid to the resolution of the $^{12}$CO(1–0) measurement using the following procedure.

The HPBW of the NRAO 12m at 115 GHz and 230 GHz is $\theta_1 = 55″$ and $\theta_2 = 32″$ respectively, the grid cell has dimensions of $\Delta \theta_c \approx \theta_2/2 \approx 15″$. This dense sampling is necessary for a reliable convolution of the $^{12}$CO(2–1) grid to the resolution of the $^{12}$CO(1–0) measurement and the subsequent estimate of their ratio.

The relation between the main beam brightness temperatures $T_{MB}^{(1)}(1 - 0)$ and $T_{MB}^{(2)}(2 - 1)$ and the true brightness temperature distributions $T_{10}$ and $T_{21}$ of the $^{12}$CO, J=1–0 and J=2–1 emission respectively can be expressed as follows:

$$T_{MB}^{(1)}(1 - 0)(\xi, n) = \frac{1}{\Omega_{MB}(1)} \int_{4\pi} P_1(\xi - \xi', n - n') T_{10}(\xi', n') d\xi' d\eta', \quad (2.3)$$

and

$$T_{MB}^{(2)}(2 - 1)(\xi, n) = \frac{1}{\Omega_{MB}(2)} \int_{4\pi} P_2(\xi - \xi', n - n') T_{21}(\xi', n') d\xi' d\eta', \quad (2.4)$$

where $P_1$, $P_2$ are the beam patterns of the NRAO 12m telescope at 115 GHz and 230 GHz respectively and $\Omega_{MB}(1)$, $\Omega_{MB}(2)$ are their volume integrals ($\Omega_{MB}(1) > \Omega_{MB}(2)$). A gaussian is a good approximation of the telescope’s main beam (Jewel 1990) for both $^{12}$CO transitions, therefore we can write

$$P_k(\xi, n) = \exp \left[ -4 \ln 2 \left( \frac{\xi^2 + n^2}{\theta_k^2} \right) \right] \quad \text{with} \quad \Omega_{MB}(k) = \frac{\pi}{4 \ln 2} \theta_k^2, \quad k = 1, 2. \quad (2.5)$$
In order to estimate the \((2-1)/(1-0)\) line ratio at the common resolution of the \(^{12}\text{CO}(1-0)\) observation we need to evaluate

\[
T_{MB}^{(1)}(2-1)(\xi, n) = \frac{1}{\Omega_{MB}(1)} \int_{4\pi} P_1(\xi' - \xi, n - n') T_{21}(\xi', n') d\xi' d\eta'.
\]  

After substituting the expressions \((k=1,2)\) from Equation 2.5 into 2.4 and 2.6 taking their Fourier transform \(F\) and dividing we obtain

\[
F\left( T_{MB}^{(1)}(2-1) \right) = F(D) \cdot F\left( T_{MB}^{(2)}(2-1) \right),
\]

where

\[
D(\xi, n) = \frac{1}{\Omega_d} \exp \left[ -4 \ln 2 \left( \frac{\xi^2 + n^2}{\theta_1^2 - \theta_2^2} \right) \right] \quad \text{with} \quad \Omega_d = \Omega_{MB}(1) - \Omega_{MB}(2) \tag{2.8}
\]

is the "differential" beam pattern.

If we now apply the inverse Fourier transform in Equation 2.7 and substitute the expression from Equation 2.8 then, for the central point \((\xi, n) = (0, 0)\) we get

\[
T_{MB}^{(1)}(2-1) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} D(\xi, n) T_{MB}^{(2)}(2-1)(\xi, n) d\xi d\eta.
\]  

The main beam brightness temperature \(T_{MB}^{(2)}(2-1)\) is sampled at only nine points within a radius \(R = \theta_1/2\). This 9-point grid provides dense enough sampling to recover all the spatial information needed to reconstruct \(T_{MB}^{(2)}(2-1)(\xi, n)\). Indeed, the beam pattern \(P_2(\xi, n)\) can be seen as the response of a spatial filter that filters out any details "finer" than the resolution limit of the telescope and from the Fourier transform of Equation 2.4 we get

\[
F\left( T_{MB}^{(2)}(2-1) \right) = \frac{1}{\Omega_{MB}(2)} F(P_2) \cdot F(T_{21})
\]  

where the Fourier transform of \(P_2\) is given by
\[ F(P_2) = \exp \left[ -\frac{\theta_2^2}{16 \ln 2} \left( k_\xi^2 + k_n^2 \right) \right]. \]  

(2.11)

According to the sampling theorem, the grid spacing \( \Delta \theta_c = \theta_2 / 2 \) corresponds to a spatial cutoff frequency of \( k_c = \pi / \Delta \theta_c \). Substituting this frequency to \( F(P_2) \) we find that, for each dimension, \( F(P_2)(k_c, 0) = F(P_2)(0, k_c) = 0.028 \). The smallness of this value guarantees that such a sampling is dense enough to recover most of the spatial frequency range of the \( T_{MB}^{(2)}(2 - 1)(\xi, n) \) distribution.

Application of the sampling theorem (Shannon 1949) for two dimensions gives the expression that interpolates \( T_{MB}^{(2)}(2 - 1)(\xi, n) \) from its discrete measurements, namely

\[
T_{MB}^{(2)}(2 - 1)(\xi, n) = \sum_{\lambda_\xi} \sum_{\lambda_n} T_{MB}^{(2)}(2 - 1)(\lambda_\xi \Delta \theta_c, \lambda_n \Delta \theta_c) \\
\times \left[ \text{sinc} \left( \frac{\pi}{\Delta \theta_c} (\xi - \lambda_\xi \Delta \theta_c) \right) \text{sinc} \left( \frac{\pi}{\Delta \theta_c} (\xi - \lambda_n \Delta \theta_c) \right) \right] 
\]

(2.12)

where \((\lambda_\xi, \lambda_n) \in (-\infty, +\infty)\) defines the grid points. Substituting Equation 2.12 into 2.9, and after some calculations, we finally get

\[
T_{MB}^{(1)}(2 - 1) = \sum_{\lambda_\xi} \sum_{\lambda_n} W(\lambda_\xi, \lambda_n) T_{MB}^{(2)}(2 - 1)(\lambda_\xi \Delta \theta_c, \lambda_n \Delta \theta_c) 
\]

(2.13)

where the "weighting" factor \( W(\lambda_\xi, \lambda_n) \) can be expressed in the form

\[
W(\lambda_\xi, \lambda_n) = \left( \int_0^1 \cos [\pi (\lambda_\xi x)] e^{-\rho^2 x^2} dx \right) \left( \int_0^1 \cos [\pi (\lambda_n x)] e^{-\rho^2 x^2} dx \right) 
\]

(2.14)

and the quantity \( \rho \) is given by

\[
\rho = \frac{\pi}{4 \sqrt{\ln 2}} \frac{\sqrt{\theta_1^2 - \theta_2^2}}{\Delta \theta_c}.
\]

(2.15)

It can be shown that in the dense sampling case, where \( \rho >> 1 \), \( W(\lambda_\xi, \lambda_n) \) is normalized, as expected, namely
We sampled the HPBW=θ₁ in a grid of nine points and from the nine weighting factors only two are independent, W(0,0) = 0.100 and W(1,0) = 0.073. The rest of the weighting factors satisfy the relations: W(1, 0) = W(0, 1) = W(0, -1) = W(-1, 0) = W(0, -1) and W(1, 1) = W(-1, -1) = W(1, -1) = W(-1, 1) = W(1, 0)²/W(0, 0).

We used Equation 2.13, and the values of the weighting factors W(λᵡ, λₙ) estimated above in order to produce the convolved spectrum \( T_{\text{cn}}(^{12}\text{CO}(2-1)) = T_{\text{MB}}^{(1)}(2-1) \) that we later use to estimate the \(^{12}\text{CO} \ (2-1)/(1-0) \) line ratio.

The \(^{12}\text{CO}(1-0) \) spectra together with the convolved \(^{12}\text{CO}(2-1) \) spectrum are shown overlayed in Figures 2.1, 2.2, 2.3, 2.4 while the spectra of the isotope transition \(^{13}\text{CO}(1-0) \) are shown overlayed with \(^{12}\text{CO}(1-0) \) in Figures 2.5, 2.6. The velocity scale for all the spectra is defined through the radio convention.\(^2\)

Examining these spectra reveals that in most cases the two transitions exhibit similar line profiles, indicating that they both sample the same CO emission and that no major pointing offsets are present. In the only case (NGC 7172) where the line profiles for J=2-1 and J=1-0 did not agree we did not estimate a \(^{12}\text{CO} \ (2-1)/(1-0) \) line ratio. In this case different beams were used and the optical size of the particular source indicates that the CO emission may be extended with respect to them. The 9-point grid makes the convolved \(^{12}\text{CO}(2-1) \) spectrum more reliable than that from a single central point even in the case of a small source with \( θ_s < θ_2 \), when a single point may seem adequate. The reason is that a grid of points can sample the emission much better than a single point in the presence of the unavoidable pointing errors.

\[\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} W(\lambda_ξ, \lambda_ν) d\lambda_ξ d\lambda_ν = 1 \]

---

\(^2\)In this convention \( V = c \frac{\nu_s - \nu}{\nu_s} \), where \( \nu_s \), \( \nu \) are the rest and the observed frequencies respectively.
Figure 2.1: The $^{12}$CO, J=2–1, J=1–0 spectra observed with the NRAO 12m telescope. The velocity is in km s$^{-1}$ (Heliocentric). The temperature scale is T$_{mb}$ in units of mK.
Figure 2.2: The $^{12}\text{CO}$, $J=2-1$, $J=1-0$ spectra observed with the NRAO 12m telescope. The velocity is in km s$^{-1}$ (Heliocentric). The temperature scale is $T_{mb}$ in units of mK.
Figure 2.3: The $^{12}$CO, J=2–1, J=1–0 spectra observed with the NRAO 12m telescope. The velocity is in km s$^{-1}$ (Heliocentric). The temperature scale is $T_{mb}$ in units of mK.
Figure 2.4: The $^{12}$CO, J=2–1, J=1–0 spectra observed with the NRAO 12m telescope (except in the case of NGC 7172, Ark 564). The velocity is in km s$^{-1}$ (Heliocentric). The temperature scale is $T_{mb}$ in units of mK.
Figure 2.5: The $^{13}$CO, $^{12}$CO J=1-0 spectra observed with the NRAO 12m telescope. The velocity is in km s$^{-1}$ (Heliocentric). The temperature scale is $T_{mb}$ in units of mK.
Figure 2.6: The $^{13}$CO, $^{12}$CO J=1–0 spectra observed with the NRAO 12m telescope. The velocity is in km s$^{-1}$ (Heliocentric). The temperature scale is $T_{mb}$ in units of mK.
2.3 The JCMT Observations

We also used the James Clerk Maxwell Telescope (JCMT)\(^3\) in two observing runs between 1994 May 7 and 1994 May 10, and between 1995 June 17 and 1995 June 18 to observe the \(^{12}\text{CO},^{13}\text{CO}\) J=2–1 lines at 230 GHz and 220 GHz respectively in some of the galaxies in our sample. The profile of the main beam of the telescope at these frequencies is closely approximated by a gaussian beam with HPBW=21". Focus and pointing were monitored frequently by observing bright quasars and planets. The pointing error (rms) was found to be \(\sim 4\"\). The JCMT observations were performed by using beam switching at the recommended rate of 1 Hz and beam-throws of 2′–3′ in azimuth. The DAS spectrometer was used with a total usable bandwidth of \(\sim 700\) MHz corresponding to a velocity coverage of \(\sim 910\) km s\(^{-1}\) at a spectral resolution of 0.625 MHz. We converted the measured temperature scale \(T^*_A\) of the JCMT spectra to the \(T_{mb}\) scale by using the relation \(T_{mb} = T^*_A/n_{mb}\) and adopting a beam efficiency of \(n_{mb} = 0.69\) (Matthews 1996) at 230 GHz. The baselines for the spectra were found to be both flat and stable during the observations.

The error is estimated according to Equation 2.1 and observations of high S/N spectral line standards showed that the temperature scale \(\text{rrms}\) factor is of the order of \(\sim 0.10\) at 230 GHz. The systematic error is \(\sim 0.10\) (Goeran Sandell, private communication). The \(^{12}\text{CO},^{13}\text{CO}\) J=2–1 spectra obtained with the JCMT are shown in Figures 2.7 and 2.8.

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\(^3\)The James Clerk Maxwell Telescope is operated by the Observatories on behalf of the Science and Engineering Research Council of the United Kingdom, the Netherlands Organization for Scientific Research, and the National Research Council of Canada.
Figure 2.7: The $^{13}\text{CO}$, $^{12}\text{CO}$ J=2–1 spectra observed with the JCMT. The velocity is in km s$^{-1}$ (Heliocentric). The temperature scale is $T_{mb}$ in units of mK.
Figure 2.8: The $^{13}$CO, $^{12}$CO J=2–1 spectra observed with the JCMT. The velocity is in km s$^{-1}$ (Heliocentric). The temperature scale is $T_{mb}$ in units of mK.
Chapter 3

Line ratios and physical conditions

3.1 The $^{12}\text{CO} (2-1)/(1-0)$ and $^{12}\text{CO}/^{13}\text{CO}$ J=1–0 line ratios

The line ratios are estimated from the main beam brightness $T_{mb}$ averaged over the entire FWZI of the line. For most of the observed galaxies, before estimating the $r_{21}=(2-1)/(1-0)$ ratio for $^{12}\text{CO}$, the $^{12}\text{CO}$ J=2–1 spectra were convolved to the resolution of the $^{12}\text{CO}$ J=1–0 spectrum in the way described in the previous chapter.

In order to check for consistency with other observers, we compared our values of $r_{21}$ with values found in the literature for Mrk 231 (Rigopoulou et al. 1996 and references therein), Arp 220 (Radford et al. 1991; Aalto et al. 1995, Rigopoulou et al. 1996), the nearby LINER NGC 6764 (Eckart et al. 1991), NGC 3227 and NGC 5033 (Braine & Combes 1992). For the first four galaxies we find excellent agreement within the reported errors and only in the case of NGC 5033 do we obtain very different values from Braine & Combes (1992) who find a ratio of $r_{21} \sim 1.6$, while we measure a much lower value of 0.58. However the CO emission in NGC 5033 is extended on scales of $\sim 20'' - 60''$ (Meixner et al. 1990) and the velocity profile of our spectra (Figure 2.3) is different than the one presented in Braine et al. (1993). This strongly indicates that the beam ($\sim 55''$) of the NRAO 12m telescope samples different gas (more extended, colder?) than the beam ($\sim 23''$) of the 30m IRAM telescope.
Note that in a few cases in the literature the spectra used to estimate \( r_{21} \) have been obtained with different resolutions. When the source size \( \theta_s \) is less than that of the smallest beam used, the intrinsic line ratio \( T_{R}(2-1)/T_{R}(1-0) \) can be reliably determined by using the equation:

\[
r_{21} = \frac{T_{R}(2-1)}{T_{R}(1-0)} = n_c(\theta_s, \theta_{10}, \theta_{21}) \frac{T_{mb}(2-1)}{T_{mb}(1-0)} = \left(\frac{\theta_s^2 + \theta_{21}^2}{\theta_s^2 + \theta_{10}^2}\right) \frac{T_{mb}(2-1)}{T_{mb}(1-0)},
\]

where \( n_c \) is the ratio of the beam-coupling factors. We assumed a gaussian source with FWHM width \( \theta_s \) and gaussian HPBW main beam widths \( \theta_{10}, \theta_{21} \) that correspond to the CO J=1–0 and J=2–1 transitions respectively. Equation 3.1 shows that, unless the source is significantly smaller than the smallest beam used, the “deconvolved” line ratio depends heavily on the adopted source size. For example, assuming that \( \theta_{10} \sim 2\theta_{21} \) the beam correction factor \( n_c \) can range from \( n_c \sim 1/4 \) (point source) to \( n_c \sim 2/5 \) (\( \theta_s = \theta_{21} \)). This is enough to change a “deconvolved” line ratio from \( r_{21} \sim 0.90 \) (for point source) to \( r_{21} \sim 0.56 \) (for \( \theta_s = \theta_{21} \)). Since the first value is usually found for warm (\( T_{\text{kin}} \geq 20 \) K) optically thick gas while the latter one is associated with cold and/or sub-thermally excited gas it is obvious that deducing gas excitation properties in such cases would yield highly ambiguous results. For this reason, whenever we use line ratio data from the literature, we include only the ones that have been obtained with matched beams, with the use of fully sampled maps, or where the source is smaller than the smaller beam used.

The \(^{12}\text{CO} \) J=1–0, J=2–1, and \(^{13}\text{CO} \) J=1–0 measurements and the associated line ratios are presented in Table 1 together with the ratios found in the literature. In the few cases where more than one reliable measurement of \( r_{21} \) is available we report the mean value and its associated formal error. In the case of Arp 220 the error reported is the dispersion of the observed values since in most of its observations the baseline is very poorly defined and the formal error is most likely an underestimate.

Except for Arp 220, for all galaxies where the \( R_{10}=^{12}\text{CO}/^{13}\text{CO} \) J=1–0 line ratio is reported, the resolution is identical or very similar to the one used to measure the
r_{21} ratio. In the case of Arp 220 the small size ($\leq 10''$, Scoville et al. 1991) of the CO emission with respect to the beams used to obtain $r_{21}$ (this work, Radford et al. 1991; Aalto et al. 1995 and Rigopoulou et al. 1996) and $R_{10}$ (Aalto et al. 1995) guarantees that these line ratios sample the same gas. We adopt $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ throughout the present study.

At the mean redshift $\langle z \rangle = 0.018$ of our Seyfert sample the resolution of $\sim 55''$ corresponds to a projected linear size of $\langle L \rangle \sim 18$ kpc, and for most (21 out of 27) of the galaxies it is $L \geq 6$ kpc. Hence the line ratios $r_{21}$ and $R_{10}$ reported in Table 3.1 probe mostly the molecular gas properties averaged over a large area of each galaxy.

In order to extend our comparison of Seyferts to other classes of galaxies we have searched the literature for extensive measurements of the $r_{21}$ ratio. A summary of the relevant details of the various surveys used in the present study can be found in Table 3.2.

From the survey of CO line ratios in starbursts by Aalto et al. (1995) we select only a small number of galaxies where similar values of the $r_{21}$ have been obtained from two independent measurements with different telescopes. The reason for doing so is that in their study different beam sizes were used to obtain ratios by fitting gaussians to the $^{12}$CO J=2–1 emission of extended sources and convolving to the resolution of the J=1–0 transition. For the reasons mentioned previously we do not consider this technique very reliable for sources whose size is comparable to the smaller beam used and even less so for a source that is extended with respect to that beam. In cases where a source has been observed more than once we use the most reliable result and if there is more than one reliable measurement we report their mean value.

For the Seyferts in our sample we find a mean (and the associated rms error of the mean) of $\langle r_{21} \rangle = 0.71 \pm 0.03$ while for each type separately we find $\langle r_{21}(\text{Sy1}) \rangle = 0.69 \pm 0.04$ and $\langle r_{21}(\text{Sy2}) \rangle = 0.73 \pm 0.04$, implying no statistically significant difference between the two types.

The average $^{12}$CO/$^{13}$CO J=1–0 line ratio for Seyferts is $\langle R_{10} \rangle = 12 \pm 1$ irrespective of Seyfert type. This value is identical to the average value found recently by Aalto et al. (1995) for the centers of most non-interacting starburst galaxies and sim-
ilar to the ones found by Young & Sanders (1986) and Sage & Isbell (1991) for nearby spirals. The galaxies NGC 5135, Arp 220 and to a lesser degree NGC 3227 seem to have values of the $R_{10}$ ratio significantly higher than the mean, confirming earlier reports by Aalto et al. (1995) that high $R_{10}$ ratios occur in strongly interacting or merging galaxies. Indeed NGC 5135 belongs to a group of seven galaxies which are gravitationally bound and lie within 1 Mpc of one another, Arp 220 is thought to be an advanced merger (Sanders et al. 1988) and NGC 3227 is a well-known Seyfert galaxy interacting with NGC 3226 (Kukula et al. 1995).
Table 3.1 The $^{12}$CO J=2–1, 1–0 and $^{13}$CO J=1–0 data

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Sy $^a$</th>
<th>$^{12}$CO(1–0) $^b$</th>
<th>$^{13}$CO(1–0) $^b$</th>
<th>$^{12}$CO(2–1) $^c$</th>
<th>$R_{10}$ $^{d1}$</th>
<th>$R_{21}$ $^{d2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mrk 938</td>
<td>2</td>
<td>10.1 ± 1.8</td>
<td>...</td>
<td>7.1 ± 1.6</td>
<td>...</td>
<td>0.80 ± 0.14 $^e$</td>
</tr>
<tr>
<td>NGC 1068</td>
<td>2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>14 ± 2 $^f$</td>
<td>1.10 ± 0.20 $^g$</td>
</tr>
<tr>
<td>Mrk 348</td>
<td>2</td>
<td>6.2 ± 0.8</td>
<td>...</td>
<td>≤ 13.9</td>
<td>...</td>
<td>≤ 0.96 $^h$</td>
</tr>
<tr>
<td>NGC 1365</td>
<td>2</td>
<td>148.7 ± 20.8</td>
<td>11.7 ± 1.9</td>
<td>81.8 ± 8.1</td>
<td>13 ± 3</td>
<td>0.55 ± 0.09</td>
</tr>
<tr>
<td>NGC 1667</td>
<td>2</td>
<td>20.6 ± 3.1</td>
<td>2.1 ± 0.5</td>
<td>12.1 ± 1.7</td>
<td>10 ± 2</td>
<td>0.59 ± 0.10</td>
</tr>
<tr>
<td>MCG 8-11-11</td>
<td>1</td>
<td>4.3 ± 0.7</td>
<td>...</td>
<td>≤ 8.75</td>
<td>...</td>
<td>≤ 1.06 $^h$</td>
</tr>
<tr>
<td>NGC 2273</td>
<td>2</td>
<td>8.2 ± 1.2</td>
<td>...</td>
<td>7.4 ± 1.4</td>
<td>...</td>
<td>0.92 ± 0.15 $^e$</td>
</tr>
<tr>
<td>Mrk 10</td>
<td>1</td>
<td>2.3 ± 0.6</td>
<td>...</td>
<td>≤ 1.1</td>
<td>...</td>
<td>≤ 0.48</td>
</tr>
<tr>
<td>NGC 2992</td>
<td>2</td>
<td>13.4 ± 2.3</td>
<td>...</td>
<td>6.6 ± 0.8</td>
<td>...</td>
<td>0.49 ± 0.10</td>
</tr>
<tr>
<td>NGC 3227</td>
<td>1</td>
<td>32.6 ± 5.6</td>
<td>2.1 ± 0.4</td>
<td>27.6 ± 4.6</td>
<td>17 ± 3</td>
<td>0.77 ± 0.14 $^g$</td>
</tr>
<tr>
<td>NGC 4051</td>
<td>1</td>
<td>36.2 ± 5.1</td>
<td>2.8 ± 0.4</td>
<td>22.0 ± 3.0</td>
<td>13 ± 3</td>
<td>0.61 ± 0.11</td>
</tr>
<tr>
<td>NGC 4388</td>
<td>2</td>
<td>22.7 ± 3.4</td>
<td>4.0 ± 1.0</td>
<td>15.9 ± 1.7</td>
<td>6 ± 2</td>
<td>0.70 ± 0.13</td>
</tr>
<tr>
<td>Mrk 231</td>
<td>1</td>
<td>10.2 ± 1.7</td>
<td>...</td>
<td>9.6 ± 1.4</td>
<td>...</td>
<td>0.98 ± 0.10 $^i$</td>
</tr>
<tr>
<td>NGC 5033</td>
<td>1</td>
<td>46.2 ± 6.5</td>
<td>5.6 ± 0.7</td>
<td>27.1 ± 2.9</td>
<td>8 ± 1</td>
<td>0.58 ± 0.10</td>
</tr>
<tr>
<td>NGC 5135</td>
<td>2</td>
<td>66.9 ± 9.9</td>
<td>2.6 ± 0.4</td>
<td>57.1 ± 6.3</td>
<td>26 ± 5</td>
<td>0.85 ± 0.14</td>
</tr>
<tr>
<td>Mrk 273</td>
<td>2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>0.80 ± 0.15 $^j$</td>
</tr>
<tr>
<td>NGC 5347</td>
<td>2</td>
<td>12.5 ± 2.2</td>
<td>...</td>
<td>11.0 ± 1.7</td>
<td>...</td>
<td>0.88 ± 0.21</td>
</tr>
<tr>
<td>Mrk 463</td>
<td>1</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>0.76 ± 0.15 $^k$</td>
</tr>
<tr>
<td>Arp 220</td>
<td>2</td>
<td>36.9 ± 5.1</td>
<td>...</td>
<td>13.3 ± 2.4</td>
<td>&gt; 20 $^l$</td>
<td>0.53 ± 0.13 $^m$</td>
</tr>
<tr>
<td>NGC 6814</td>
<td>1</td>
<td>59.5 ± 8.2</td>
<td>8.1 ± 1.2</td>
<td>35.8 ± 3.9</td>
<td>7 ± 1</td>
<td>0.60 ± 0.10</td>
</tr>
<tr>
<td>IC 5135</td>
<td>2</td>
<td>61.7 ± 9.2</td>
<td>...</td>
<td>31.2 ± 3.7</td>
<td>8 ± 1 $^l$</td>
<td>0.50 ± 0.10</td>
</tr>
<tr>
<td>NGC 7469</td>
<td>1</td>
<td>35.0 ± 5.2</td>
<td>...</td>
<td>16.9 ± 2.2</td>
<td>...</td>
<td>0.48 ± 0.09</td>
</tr>
<tr>
<td>Mrk 533</td>
<td>2</td>
<td>13.7 ± 2.2</td>
<td>1.6 ± 0.4</td>
<td>10.6 ± 1.6</td>
<td>9 ± 2</td>
<td>0.77 ± 0.16</td>
</tr>
</tbody>
</table>

---

Table 3.1—Continued

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Sy</th>
<th>$^{12}$CO(1–0) $^b$</th>
<th>$^{13}$CO(1–0) $^b$</th>
<th>$^{12}$CO(2–1) $^c$</th>
<th>$R_{10}^{d1}$</th>
<th>$r_{21}^{d2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 6764 (LINER)</td>
<td>24.9 ± 3.2</td>
<td>2.25 ± 0.49</td>
<td>24.5 ± 3.2</td>
<td>11 ± 3</td>
<td>0.98 ± 0.19</td>
<td></td>
</tr>
<tr>
<td>Ark 564</td>
<td>1</td>
<td>≤ 5.4</td>
<td>...</td>
<td>9.9 ± 2.4</td>
<td>...</td>
<td>≥ 0.50$^h$</td>
</tr>
<tr>
<td>I Zw 001</td>
<td>1</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>9 ± 2$^n$</td>
<td>0.73 ± 0.11$^o$</td>
</tr>
<tr>
<td>Mrk 817</td>
<td>1</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>0.72 ± 0.14$^k$</td>
</tr>
</tbody>
</table>

$^a$ Seyfert type.

$^b$ The FWZI-averaged main beam brightness $\langle T_{mb}\rangle_{\Delta V}$ (mK).

$^c$ The FWZI-averaged main beam brightness (mK) of the convolved $^{12}$CO(2–1) spectrum (see Equation 2.13).

$^d$ The $^{12}$CO/$^{13}$CO J=1–0 and the $^{12}$CO (2–1)/(1–0) line ratios.

$^e$ The mean of two independent values from two measurements of $^{12}$CO(2–1) with the NRAO 12m telescope and the JCMT (source size $\theta_s < \theta_{JCMT}$).

$^f$ Papadopoulos et al. (1996), Young & Sanders (1986).


$^h$ Only one $^{12}$CO(2–1) point was observed, assumed size $\theta_s \leq 1/3(\theta_{opt})$.

$^i$ This work and values quoted in Rigopoulou et al. (1996).

$^j$ Rigopoulou et al. (1996)

$^k$ Alloin et al. (1992)

$^l$ Aalto et al. (1995)

$^m$ This work, Radford et al. (1991), Aalto et al. (1995), Rigopoulou et al. (1996).

$^n$ Eckart et al. (1994)

$^o$ Barvainis et al. (1989) and Alloin et al. (1992)
Table 3.2 Observations of the $^{12}$CO (2–1)/(1–0) ($r_{21}$) ratio

<table>
<thead>
<tr>
<th>Reference</th>
<th>$N_{\text{orig}}^a$</th>
<th>Technique$^b$</th>
<th>$N_{\text{sel}}^c$</th>
<th>Type$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>27</td>
<td>9-point grid, $\theta_s &lt; \theta_{\text{min}}$</td>
<td>22</td>
<td>Seyferts</td>
</tr>
<tr>
<td>Braine &amp; Combes (1992)</td>
<td>36</td>
<td>9-point grid</td>
<td>34</td>
<td>Various</td>
</tr>
<tr>
<td>Chini et al. (1992)</td>
<td>9</td>
<td>Matched beams</td>
<td>4</td>
<td>Starbursts</td>
</tr>
<tr>
<td>Aalto et al. (1995)</td>
<td>22</td>
<td>Multiple observations</td>
<td>3</td>
<td>Starbursts</td>
</tr>
<tr>
<td>Radford et al. (1991)</td>
<td>4</td>
<td>$\theta_s &lt; \theta_{\text{min}}$</td>
<td>2</td>
<td>Starbursts/AGN</td>
</tr>
<tr>
<td>Casoli et al. (1988)</td>
<td>2</td>
<td>$\theta_s &lt; \theta_{\text{min}}$</td>
<td>1</td>
<td>Starburst</td>
</tr>
<tr>
<td>Various studies$^e$</td>
<td>10</td>
<td>Matched beams, Maps$^f$</td>
<td>4</td>
<td>Starbursts</td>
</tr>
</tbody>
</table>

$^a$ The number of galaxies in the original sample.

$^b$ The observing technique used for the galaxies we select.

$^c$ The number of the galaxies selected.

$^d$ Type of activity in selected galaxies, Various=Starbursts, LINERs, Quiescents.

$^e$ For a summary see Aalto (1995), pg 375 and references therein.

$^f$ Maps = Fully sampled $^{12}$CO(2–1) map convolved to the resolution of $^{12}$CO(1–0).
3.2 The $^{12}$CO/$^{13}$CO J=2–1 ratios

Table 3.3 presents the $^{12}$CO, $^{13}$CO J=2–1 JCMT measurements and their ratios. We also list the quantity $Q$ for all the galaxies (except I Zw 001), which is defined as follows:

$$Q = \frac{\int_{4\pi} P_n(JCMT) T_R \, d\Omega}{\int_{4\pi} P_n(12m) \, d\Omega} = \frac{\left(\frac{\theta_{mb}(JCMT)}{\theta_{mb}(12m)}\right)^2}{\frac{T_{mb}(JCMT)}{T_{cn}(12m)}},$$  \hspace{1cm} (3.2)

where $P_n(JCMT)$ and $\theta_{mb}(JCMT)$ are respectively the beam pattern and the corresponding HPBW for the JCMT telescope at a frequency of $\sim 215$ GHz, while $P_n(12m) \, d\Omega$ and $\theta_{mb}(12m)$ are the effective beam pattern and the corresponding HPBW ($\sim 55''$) for the convolved spectrum of the $^{12}$CO(2–1) transition observed with the 12m telescope. The quantities $T_{mb}$ and $T_R$ are the velocity-averaged main beam brightness and intrinsic brightness temperatures of the $^{12}$CO J=2–1 transition and $T_{cn}(12m)$ is the convolved spectrum of $^{12}$CO J=2–1 obtained from the 9-point maps with the NRAO 12m telescope. From the definition of $Q$ it is apparent that, for sources resolved by the smaller JCMT beam $Q < 1$, while for the unresolved ones $Q \sim 1$.

Table 3.3 shows that IC 5135 and NGC 7469 are unresolved by the JCMT beam and this is also the case for I Zw 001, the most distant Seyfert in our sample, since the telescope beams used (Barvainis et al. 1989; Alloin et al. 1992; Eckart et al. 1994) were larger than the CO emitting region. The statistics on the $^{12}$CO/$^{13}$CO J=2–1 ratio $R_{21}$ is poorer than for $R_{10}$ or $r_{21}$ but we find $\langle R_{21} \rangle = 13 \pm 1$, which is identical to the value found by Aalto et al. (1995) for their sample of starburst nuclei. The same mean value is found for Sy2 and Sy1 galaxies separately. Once again we measure the highest values of $R_{21}$ towards strongly interacting or merging galaxies like NGC 3227 and Arp 220.

For NGC 5135 the ratio $R_{21} = 13$ is significantly lower than $R_{10} = 26$ (Table 3.1). Even though for this galaxy $Q$ is slightly less than unity the profiles of the two spectra of the $^{12}$CO J=2–1 transition (Figures 2.3, 2.7) are very similar, so it
is possible that the two beams sample the same gas. Then the $^{13}$CO (2–1)/(1–0) ratio is $r_{21}(^{13}$CO) = $(R_{10}/R_{21}) \times r_{21} = 1.7 \pm 0.5$, comparable, within the errors, to $\langle r_{21}(^{13}$CO) $\rangle = 1.3$ found by Aalto et al. (1995) towards the centers of starbursts. The only other Seyfert unresolved by the JCMT beam with both J=2–1, 1–0 transitions of $^{13}$CO measured is IC 5135, a luminous ($L_{\text{FIR}} \sim 10^{11}L_\odot$) far-infrared source. The nuclear region of this galaxy exhibits both the characteristics of a Seyfert 2 and a very intense starburst (Shields & Filipenko 1990). We find $r_{21}(^{13}$CO) = $0.36 \pm 0.10$, a very low value when compared to the one measured for NGC 5135 and the mean value reported by Aalto et al. (1995). This value as well as $r_{21} = 0.50$ correspond to linear scales of $\sim 6$ kpc (21" at z=0.016) and therefore it seems that despite the intense nuclear activity in IC 5135 the global CO emission arises from cold ($T_{\text{kin}} \leq 10$ K) and possibly sub-thermally excited gas. In the next section we discuss the possibility that such low line ratios in IR-luminous galaxies are solely due to a large filling factor of an extended cold gas phase with respect to a warm gas phase that is confined in the inner 0.5–1 kpc.
<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Sy(^a)</th>
<th>(^{12})CO(2−1)(^b)</th>
<th>(^{13})CO(2−1)(^b)</th>
<th>(R_{21})(^c)</th>
<th>(Q)(^f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1365</td>
<td>2</td>
<td>314.5 ± 37.7</td>
<td>32.5 ± 4.2</td>
<td>10 ± 2</td>
<td>0.55 ± 0.10</td>
</tr>
<tr>
<td>NGC 3227</td>
<td>1</td>
<td>127.5 ± 15.3</td>
<td>5.01 ± 1.4</td>
<td>25 ± 8</td>
<td>0.68 ± 0.15</td>
</tr>
<tr>
<td>NGC 4051</td>
<td>1</td>
<td>130.1 ± 16.9</td>
<td>9.13 ± 2.2</td>
<td>14 ± 4</td>
<td>0.55 ± 0.11</td>
</tr>
<tr>
<td>NGC 5033</td>
<td>1</td>
<td>104.1 ± 12.5</td>
<td>16.3 ± 3.5</td>
<td>6 ± 1</td>
<td>0.54 ± 0.09</td>
</tr>
<tr>
<td>NGC 5135</td>
<td>2</td>
<td>320.3 ± 41.6</td>
<td>25.2 ± 3.5</td>
<td>13 ± 2</td>
<td>0.81 ± 0.14</td>
</tr>
<tr>
<td>Arp 220</td>
<td>2</td>
<td>...</td>
<td>3.2 ± 0.6</td>
<td>18 ± 3(^d)</td>
<td>...</td>
</tr>
<tr>
<td>IC 5135</td>
<td>2</td>
<td>356.6 ± 42.8</td>
<td>33.3 ± 4.3</td>
<td>11 ± 2</td>
<td>1.10 ± 0.20</td>
</tr>
<tr>
<td>NGC 7469</td>
<td>1</td>
<td>137.2 ± 17.8</td>
<td>9.3 ± 2.3</td>
<td>15 ± 4</td>
<td>1.04 ± 0.21</td>
</tr>
<tr>
<td>I Zw 001</td>
<td>1</td>
<td>...</td>
<td>...</td>
<td>≥ 6(^e)</td>
<td>...</td>
</tr>
</tbody>
</table>

\(^a\) Seyfert type

\(^b\) The FWZI-averaged main beam brightness temperature \(\langle T_{mb}\rangle_{\Delta v}\)(mK).

\(^c\) The line ratio \(^{12}\)CO/\(^{13}\)CO J=2−1 of the respective \(\langle T_{mb}\rangle_{\Delta v}\).

\(^d\) The average of two values resulting from one NRAO 12m Telescope and one IRAM measurement of the \(^{12}\)CO(2−1) (Radford et al. 1991) and our JCMT \(^{13}\)CO(2−1) measurement. The assumed source size is \(\theta_s = 10''\).

\(^e\) Eckart et al. (1994)

\(^f\) The common line-width used for the evaluation of \(Q\) is somewhat wider than the one used to estimate the \(R_{21}\) ratio (which involves the weaker \(^{13}\)CO line) so that the emission from the most extreme velocity range (usually located the furthest from the nucleus) will be included.
3.3 The state of the molecular gas in Seyferts

It has been suggested by Aalto et al. (1995) that $R_{10}$ is a measure of molecular cloud disruption in starburst nuclei. According to this picture the large molecular gas densities ($\Sigma(H_2) > 10^4$ M$_\odot$ pc$^{-2}$) found in the centers of very IR-luminous ($L_{\text{FIR}} > 10^{11}$ L$_\odot$) mergers lead to large pressures and turbulent line widths. This, together with the proximity of the circumnuclear gas to a steep gravitational potential, are responsible for generating a diffuse, optically thin (i.e., the $^{12}$CO J=1–0 transition has $T_{\text{rot}}^{(12)} \approx 1$) molecular gas phase with $R_{10} > 20$. In the same study it has been proposed that intermediate ratios $10 \leq R_{10} \leq 15$ originate in the inner kpc of less extreme starbursts with more moderate gas surface densities (i.e., $\Sigma(H_2) \leq 10^3$ M$_\odot$ pc$^{-2}$), and small ratios $R_{10} \approx 6$ are a signature of a disk population of cold, optically thick molecular clouds residing in a quiescent environment.

It is interesting to note that, except for Arp 220, all the Seyferts in Table 3.1 with $R_{10} \leq 8$ also have $r_{21} \leq 0.7$. Following Aalto et al. (1995) we argue that these line ratios indicate that our large beam samples a significant part of the disk population of clouds in many of the galaxies in our sample. On the other hand, the archetypal Sy2 galaxy NGC 1068 with $r_{21} \sim 1$ (Braine & Combes 1992) has $R_{10} = 14$ for the inner $\sim 30''$, which is the approximate size of the central starburst (Wilson & Ulvestand 1982; Telesco et al. 1984; Telesco & Dreher 1988; Atherton et al. 1985). The excitation of the molecular gas in this case may be more characteristic of gas residing in the circumnuclear regions of less extreme starbursts.

We must also mention that high $R_{10}$ ratios could be the result of an intrinsically high $[^{12}\text{CO}/^{13}\text{CO}]$ abundance ratio (Casoli et al. 1992). Such abundances can be produced because of selective nucleosynthesis by massive stars (Henkel & Mauersberger 1993) and/or selective photodissociation of the $^{13}$CO molecules in the UV-intense starburst environment (e.g., Fuente et al. 1993). These phenomena are expected to occur mainly in the inner regions of starburst galaxies rather than the more quiescent disk and their effect would be to introduce a wider range of values for $R_{10}$ with respect to the $r_{21}$ ratio which does not depend on the $[^{12}\text{CO}/^{13}\text{CO}]$ abundance.
3.3.1 An excitation gradient

The low mean ratio \( \langle r_{21} \rangle = 0.71 \) found for Seyfert galaxies with respect to \( \langle r_{21} \rangle = 0.90 \) found towards the centers of nearby spirals (Braine & Combes 1992) and starbursts (Aalto et al. 1995 and references therein) may signify a difference in their respective molecular gas excitation. Indeed, for many Seyferts observed (10 out of 26) we measure values of \( r_{21} \) as low as \( \sim 0.5 - 0.6 \). Assuming optically thick and thermalized levels up to \( J=2 \), a ratio \( r_{21} = 0.7 \) corresponds to an excitation temperature of \( T_{\text{ex}} = 7 \text{ K} \) which can probably be maintained by cosmic ray heating (Goldsmith & Langer 1978). Hence the ratios \( r_{21} \) observed for Seyferts correspond to either very cold and thermalized or (when \( r_{21} < 0.7 \)) subthermally excited gas. This is in contrast with the warm \( (T_{\text{kin}} > 20 \text{ K}) \) optically thick gas that is usually associated with \( r_{21} \sim 0.90 \).

Intuitively, one expects the gas in actively star-forming galaxies to be warmer than in quiescent ones since the intense UV radiation from massive stars and the enhanced gas turbulence present especially in starburst nuclei are expected to heat the gas. From this perspective, the lower values of \( r_{21} \) observed in Seyferts seem to contradict the notion that Seyfert galaxies as a whole have elevated rates of star formation compared to similar field galaxies (Maiolino et al. 1995). However, a problem with such a straightforward interpretation arises from the fact that the beams used in the various measurements of the \( r_{21} \) line ratio correspond to different linear sizes in different galaxy samples. In the case where a radial gas excitation gradient is present across a galaxy, different \( r_{21} \) ratios will then be measured for different beam sizes.

Figures 3.1 and 3.2 show the frequency distributions of \( r_{21} \) and \( \Omega_s/\Omega_{\text{mb}} \) respectively for four classes of galaxies, namely Seyferts, starbursts, LINERs and quiescent galaxies (i.e., with no AGN or prominent starburst). \( \Omega_s \) is the size of the source derived from optical measurements and \( \Omega_{\text{mb}} \) is the main beam solid angle of the corresponding CO observations.
Figure 3.1: The frequency distribution of the $\frac{r_{21}}{r_{10}} = \frac{(2-1)}{(1-0)}$ ratio of $^{12}\text{CO}$ for Seyferts, Starbursts, LINERs and quiescent galaxies.
Figure 3.2: The frequency distribution of the $\Omega_s/\Omega_{mb}$ ratio for Seyferts Starbursts, LINERs and quiescent galaxies with measured $r_{21}$ ratios. $\Omega_s = D_{25}(1) \times D_{25}(2)$ where $D_{25}(1, 2)$ are the dimensions of the source at the surface brightness level of $\mu_B = 25.0$ B - mm/ss obtained from the RC3 catalog. $\Omega_{mb} = (\pi/4) \theta_{HPBW}^2$ is the main beam of the telescope used.
From Figure 3.1, it is apparent that Seyferts have systematically lower line ratios than quiescent galaxies and a similar trend is seen for the sample of starburst galaxies, although in their case $r_{21}$ does span the whole range of values found for the sample of quiescent galaxies. The LINERs and even more so the quiescent galaxies seem to be more uniformly distributed around the value $\langle r_{21} \rangle \approx 0.9$. A comparison of the frequency distributions of $r_{21}$ and $\Omega_a/\Omega_{mb}$ in Figures 3.1 and 3.2 reveal a broad correlation between these two variables in the case of Seyferts and starburst galaxies where there seems to be a strong tendency for $r_{21}$ and $\Omega_a/\Omega_{mb}$ to cluster towards the lower end of their distributions. From the same figures, we see that similar trends, if they exist, are much less pronounced in the samples of LINERs and quiescent galaxies.

A gas excitation gradient consisting of warm gas in the central regions and cold gas in the outer regions can easily account for these effects. In such a case, a small beam will sample predominantly the warm nuclear component producing high $r_{21}$ ratios while a larger beam will average-in cold gas, thus result in lower observed $r_{21}$ ratios.

Such molecular gas excitation gradients in galaxies have already been found in numerous cases. In particular, studies of the molecular gas in the center of the Galaxy (Gusten et al. 1985; Bally et al. 1988; Stark et al. 1991; Binney et al. 1991; Sregel & Blitz 1992) have revealed that the environment there is more extreme in terms of kinematics and gas excitation compared to the more quiescent disk. A similar picture emerges for the center and the disk of other galaxies (e.g., Knapp et al. 1980; Wall & Jaffe 1990; Wall et al. 1991; Eckart et al. 1991; Harris et al. 1991; Wall et al. 1993; Wild et al. 1992; Aalto et al. 1995) and particularly for starbursts where intense star formation activity is found within the inner kpc (e.g., Scoville et al. 1991; Wynn-Williams & Becklin 1993) and it is likely to heat the molecular gas.

The effect of such gradients on the observed $r_{21}$ ratios is even better demonstrated in Figure 3.3 where the averages $\langle r_{21} \rangle$, $\langle \Omega_a/\Omega_{mb} \rangle$ for whole classes of galaxies are plotted. Such averaging is expected, to a certain extent, to “smooth-out” the particular details of the gas excitation gradient that can be different in individual galaxies while retaining only its broader features that are expected to be common.

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Figure 3.3: The average $^{12}$CO $r_{21}=(2-1)/(1-0)$ line ratio versus the average $\Omega_{s}/\Omega_{mb}$ (see text). The error bars are 1σ standard deviation of the mean. The first seven points of the graph have a correlation coefficient of $r_{corr}=90\%$ with a probability that their configuration arose by chance less than 5%. The line showing comes from Eq. 3.4 (see text) for $L_{s}=20$ kpc, $L_{w}=0.9$ kpc. The line ratios are $r_{21}^{(w)}=0.90$, $r_{21}^{(c)}=0.66$ and $T_{b}(1-0)_{(w)}/T_{b}(1-0)_{(c)}=3$. A set of conditions that can reproduce these ratios fairly closely is the following:

**Cold gas:** $T_{kin}=9$ K, $n(H_{2})=10^{3}$ cm$^{-3}$, $X/(dV/dr)=3 \times 10^{-5}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$.

**Warm gas:** $T_{kin}=26$ K, $n(H_{2})=3 \times 10^{3}$ cm$^{-3}$, $X/(dV/dr)=3 \times 10^{-6}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$.
Assuming that the cold gas phase fills-up the telescope beam and the filling factor of the warm gas in the inner region is \( f_w = \Omega_w / \Omega_{mb} \), then the observed \( r_{21} \) line ratio can be expressed as follows:

\[
r_{21} = r_{21}^{(c)} \left[ \frac{1 + f_w \frac{T_b(2-1)(w)}{T_b(2-1)(c)}}{1 + f_w \frac{T_b(1-0)(w)}{T_b(1-0)(c)}} \right]
\]

(3.3)

where \((c)=\)cold gas phase, \((w)=\)warm gas phase, and \(T_b\) is the brightness temperature.

It is \( f_w = (L_w/L_{mb})^2 \), where \( L_w \) is the diameter of the central star forming region and \( L_{mb} \) the projected linear diameter corresponding to the telescope main beam. In most cases we expect \( f_w \ll 1 \); hence, for reasonable temperature ratios between the warm and the cold gas phase, we can approximate Equation 3.3 as follows

\[
r_{21} = \left[ \left( \frac{r_{21}^{(w)} - r_{21}^{(c)}}{L_w/L_s} \right)^2 \frac{T_b(1-0)(w)}{T_b(1-0)(c)} \right] x + r_{21}^{(c)}
\]

(3.4)

where we have set \( f_w = (L_w/L_s)^2 \), with \( x = (L_s/L_{mb})^2 = \Omega_s/\Omega_{mb} \).

In Figure 3.3 it is shown that, for a typical set of parameters characterizing the warm and the cold gas phase, Equation 3.4 easily accounts for the correlation between \( \langle r_{21} \rangle \) and \( \langle \Omega_s/\Omega_{mb} \rangle \). Predictably the fit seems to fail when the projected linear size of the beam becomes \( L_{mb} \sim 1 \) kpc \((x \sim 250)\), i.e., comparable to the typical size of a nuclear starburst.

### 3.3.2 A similar gas excitation for Seyferts and starbursts?

The previous discussion makes it apparent that caution is needed when using observed line ratios to demonstrate differences or similarities of molecular gas properties among galaxies over large scales. Nevertheless there are some indications that Seyferts may be sharing more common features in their global gas excitation conditions with starbursts rather than quiescent galaxies. The frequency distributions of \( r_{21} \) (Figure 3.1 ) for Seyferts and starbursts seem to be similar in their overlapping region. The results from a Kolmogorov-Smirnov (K-S) test performed for the distribution of \( r_{21} \) in Seyfert, starburst and quiescent galaxies are shown in Table 3.4.
Table 3.4 K–S results

<table>
<thead>
<tr>
<th>Sample pair</th>
<th>( \left( \frac{\Omega_s}{\Omega_{mb}} \right)_{\text{max}} )</th>
<th>( N_e ) (^b)</th>
<th>( D_m ) (^c)</th>
<th>( Q_{KS}(D_m, N_e) ) (^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seyferts &amp; Starbursts</td>
<td>whole range</td>
<td>10</td>
<td>0.27</td>
<td>35%</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>100</td>
<td>7</td>
<td>0.25</td>
<td>89%</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>50</td>
<td>6</td>
<td>0.17</td>
<td>99%</td>
</tr>
<tr>
<td>Seyferts &amp; Quiescents</td>
<td>whole range</td>
<td>10</td>
<td>0.45</td>
<td>3%</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>200</td>
<td>9</td>
<td>0.49</td>
<td>3%</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>100</td>
<td>5</td>
<td>0.66</td>
<td>1%</td>
</tr>
</tbody>
</table>

\(^a\) The maximum value of \( \Omega_s/\Omega_{mb} \) of the samples compared.

\(^b\) \( N_e = N_1N_2/(N_1 + N_2) \) is the effective number of data points. The K–S test is applicable for \( N_e \geq 4 \) (Stephens 1970).

\(^c\) \( D_m = \max|S_1(x)−S_2(x)| \), where \( S_1(x) \), \( S_2(x) \) are the two cumulative distributions.

\(^d\) The K–S significance estimator.

In this table we see that the probability \( Q_{KS} \) that the two samples of \( r_{21} \) for Seyferts and starbursts are drawn from the same distribution increases up to 99% as we restrict the range of \( \Omega_s/\Omega_{mb} \) of the samples to lower values where most of the Seyferts are found. On the contrary a similar comparison between Seyfert and quiescent galaxies yields \( Q_{KS} \leq 3\% \).

This picture is consistent with the notion that Seyferts and starbursts are more likely to harbor an intense nuclear (≤ 1 kpc) starburst that warms the gas in that region while more quiescent types harbor star formation that is usually more spread out in the disk, thus establishing a somewhat different pattern of global molecular gas excitation.
3.4 Molecular gas in Seyferts: The cold gas phase

In order to probe the properties of the cold gas component we chose IC 5135 (Sy2) as our template galaxy. The reason is twofold, namely (a) the low line ratio $r_{21}$ implies that its CO emission is dominated by very cold and/or sub-thermally excited gas, and (b) the transitions $^{12}\text{CO}$ $J=1-0$, $J=2-1$ observed with the NRAO 12m and the transitions $^{13}\text{CO}$, $^{12}\text{CO}$ $J=2-1$ observed with the JCMT seem to sample the same gas ($Q \sim 1$) over scales of $\sim 6$ kpc. Hence they can be used together to constrain the average gas properties over a large area of this galaxy.

The line ratios $r_{21} = 0.50 \pm 0.10$, $R_{10} = 8 \pm 1$ observed in IC 5135 are considered characteristic of a disk population of clouds (e.g., Aalto 1994; Aalto 1995; Eckart 1991). The $R_{21} = 11 \pm 2$ measured with the JCMT corresponds to $r_{21}(^{13}\text{CO}) = (R_{10}/R_{21})r_{12} = 0.36 \pm 0.11$. Line ratios as low as these are a strong indication of sub-thermal excitation since the assumption of thermal excitation (LTE) of the levels up to $J=2$ leads to $T_{\text{kin}} = 4$ K, which is below the minimum value of $T_{\text{min}} \sim 7$ K that can be sustained by cosmic ray heating (Goldsmith & Langer 1978). Allen & Lequeux (1993) have reported observations of the $^{12}\text{CO}$ $J=1-0$, 2–1 transitions from two dust clouds in the inner disk of M 31 where they find massive (few $\times 10^7 \text{ M}_\odot$) molecular clouds with $r_{21} = 0.3 \sim 0.4$, similar to the $r_{21}$, $r_{21}(^{13}\text{CO})$ ratios that we measure for the global ($\geq 6$ kpc) CO emission in IC 5135. Allen et al. (1995) conclude that the properties of such clouds can be understood as resulting mainly from a very low UV radiation field and cosmic ray density that allow the average kinetic temperature to drop to very low ($T_{\text{kin}} \leq 5$ K) values. For such conditions an LTE solution that fits the observed line ratios in IC 5135 is still viable but unlike non-LTE solutions it is not density-sensitive since it can correspond to any $n(\text{H}_2) \geq 10^4 \text{ cm}^{-3}$, the thermalization density of the $J=2-1$ transition in the optically thin regime.

Adequate description of sub-thermal excitation conditions requires full solution of the rate equations for the populations of the rotational energy levels of CO. For this purpose we used a Large Velocity Gradient (LVG) model (e.g., Richardson 1985) with a code written by Jessica Arlett and Lorne Avery. In such models it is assumed
that the systematic motions rather than the local thermal velocities dominate the observed linewidths of the molecular clouds. This greatly simplifies the solution of the rate equations since photons can interact with the radiating gas only locally. The model employed here assumes spherical clouds that collapse according to the velocity law $V(r) \propto r$ and it includes the rate equations for three CO isotopes and rotational levels up to $J=10$. It has been shown (e.g., de Jong et al. 1975; Richardson 1985) that different cloud geometries (plane versus spherical) and velocity laws result in variations of the deduced molecular gas properties that are less than or of the order of the typical observational errors. Throughout our modeling we assume an abundance of $[^{12}\text{CO}/^{13}\text{CO}]=60$ (Langer & Penzias 1993), which represents a good average value for most of the scales of CO emission observed in this survey.

For the case of IC 5135, we conducted a wide search of the LVG parameter space $(T_{\text{kin}}, n(\text{H}_2), \Lambda)$, where $\Lambda = X(dV/dr)^{-1}$ with $X=[^{12}\text{CO}/\text{H}_2]$ being the abundance of $^{12}\text{CO}$ relative to $\text{H}_2$ and $dV/dr$ the velocity gradient. Then we employed a $\chi^2$ minimization technique in order to find the optimum set of parameters that reproduces the measured $r_{21}$, $R_{10}$ and $R_{21}$ line ratios. The results are summarized in Table 3.5.

We find that the best fit corresponds to cold gas ($T_{\text{kin}} = 7$ K) with optically thick ($\tau_{10} \sim \tau_{21} \sim 10$) and thermalized $^{12}\text{CO}$ emission. The significant optical depth of this isotope and the resulting radiative trapping thermalizes its emission up to the $J=2$ level at an effective critical density $n(\text{H}_2)_{\text{crit}} \sim n(\text{H}_2)_{\text{crit}}(J=2-1)/\tau_{21} \sim 10^3$ cm$^{-3}$. For the same set of conditions, the $^{13}\text{CO}$ isotope is found to be optically thin ($\tau_{10} \sim \tau_{21} \sim 0.2$) with its $J=2-1$ transition sub-thermally excited ($T_{\text{ex}}(2-1)/T_{\text{kin}}=0.60$) as expected. Table 3.5 also shows that even if we adopt the “warmest” values $r_{21} = 0.6$, $R_{10} = R_{21} = 9$ (so that $r_{21}(^{13}\text{CO}) = 0.6$) allowed by the errors, the optimum set of parameters $(T_{\text{kin}}, n(\text{H}_2), \Lambda)$ do not change except for the gas temperature, which nevertheless remains low.

The contour maps in Figure 3.4 display the contours of $\log X$ overlaid on the parameter space $(n(\text{H}_2), \Lambda)$ for $T_{\text{kin}} = 7, 15$ K.
Table 3.5 IC 5135: LVG model results

<table>
<thead>
<tr>
<th>$R_{21}^{(LVG)}$</th>
<th>$R_{10}^{(LVG)}$</th>
<th>$R_{21}^{(LVG)}$</th>
<th>$T_{\text{kin}}$ (K)</th>
<th>$\chi_{\text{min}}$ $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50 (0.60)</td>
<td>8 (8)</td>
<td>11 (15)</td>
<td>5 → 16</td>
<td>1.14 (7, 3, 3)</td>
</tr>
<tr>
<td>0.50 (0.63)</td>
<td>8 (10)</td>
<td>11 (21)</td>
<td>17 → 26</td>
<td>2.54 (17, 0.3, 100)</td>
</tr>
<tr>
<td>0.60 (0.67)</td>
<td>9 (9)</td>
<td>9 (16)</td>
<td>7 → 16</td>
<td>1.46 (9, 3, 3)</td>
</tr>
<tr>
<td>0.60 (0.84)</td>
<td>9 (9)</td>
<td>9 (15)</td>
<td>17 → 26</td>
<td>2.05 wide range$^c$</td>
</tr>
</tbody>
</table>

Note: The grid of the LVG models we used has the increments $\Delta T_{\text{kin}} = 1$ K, $\Delta \log[n(H_2)] = 0.5$ and $\Delta [\log \Lambda] = 0.5$. The density range is $n(H_2) = (0.1 - 10^5) \times 10^3$ cm$^{-3}$ and $\Lambda = X/(dV/dr) = (0.1 - 10^2) \times 10^{-6}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$. The fit was performed by minimizing $\chi^2 = \sum_i \frac{1}{\sigma_i^2} [R_{\text{obs}}^{(i)} - R_{\text{theor}}^{(i)}]^2$, where $R_{\text{obs}}^{(i)}$ and $\sigma_i$ are the observed line ratios and their associated 1σ errors and $R_{\text{theor}}^{(i)}$ are the theoretical ones deduced from the LVG model.

$^a$ The minimum value of $\chi$ and the corresponding LVG parameters in units of K, $10^3$ cm$^{-3}$, $10^{-6}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$.

$^b$ The estimated line ratios from the LVG model with the smallest $\chi^2$.

$^c$ The $\chi_{\text{min}}$ found for every $T_{\text{kin}}$ is almost constant.
Figure 3.4: Two contour maps of $\log \chi$ with $T_{\text{kin}} = 7, 15$ K for IC 5135. The minimum value is $\log \chi_{\text{min}} = 0.056$ ($T_{\text{kin}} = 7$ K), the contour spacing is $\Delta \log \chi = 0.2$ and $n(\text{H}_2)$, $\Lambda$ are expressed in logarithmic scale in units of $\text{cm}^{-3}$ and $(\text{km s}^{-1} \text{ pc}^{-1})^{-1}$ respectively.
Cold and very likely subthermally excited gas seems to also dominate the emission in the Syl galaxy NGC 7469 where we measure $r_{21} = 0.48$ (Table 1). This galaxy, like IC 5135, is unresolved ($Q \sim 1$) by the JCMT beam and thus the $r_{21}$ (NRAO 12m) and $R_{21}$ (JCMT) ratios probe the same beam-averaged physical properties of the gas. An LTE solution corresponds to $T_{\text{kin}} = 3 - 4$ K, while a typical non-LTE solution from LVG modeling is $T_{\text{kin}} = 10$ K, $n(H_2) \sim 3 \times 10^2$ cm$^{-3}$ and $\Lambda \sim 1 \times 10^{-4}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$.

### 3.5 Molecular gas in Seyferts: The warm gas phase

Unlike the cold molecular gas residing in the more quiescent disk environment whose excitation properties may not be very diverse, the wide range of star-forming activity observed in the central regions of starbursts seems to give rise to a wide range of physical properties of the associated warm molecular gas.

In very IR-luminous mergers/interacting galaxies with high values of $R_{10}$ the average conditions of the molecular gas can be even more extreme and in a few cases (see Aalto et al. 1995) the observed line ratios may imply the presence of a two-phase gas in the central starbursting regions of these galaxies. The galaxies NGC 5135 and Arp 220 in our sample have values of $R_{10} > 20$ but in our survey only NGC 5135 is observed in both $J=2-1$, $J=1-0$ for the $^{12}$CO, $^{13}$CO isotopes. The ultraluminous merger galaxy Arp 220 has been studied by Aalto et al. (1995) where they use it as an extreme example to show that a single gas phase cannot account for the average $R_{10} = 10 - 15$, $r_{21}(^{13}$CO) $\approx 1.3$ and $r_{21} \approx 0.9$ line ratios found towards the centers of starbursts.

We argue that Arp 220 is a special case of a starburst where a particularly low $r_{21} = 0.53$ and a possibly high $r_{21}(^{13}$CO) $> 1$ (Casoli et al. 1992) line ratio make it unlikely that a single gas phase can account for both (Aalto et al. 1995). However this is not the case for the average values of $R_{10}$, $r_{21}$, $r_{21}(^{13}$CO) observed in starburst nuclear regions where we find that a single gas phase can still reproduce these ratios fairly well. In order to examine the molecular gas properties of such systems in more
detail we conducted LVG modeling for three characteristic cases, namely NGC 5135 and an “average” starburst for $R_{10} = 10, 15$. For NGC 5135 we have assumed that the JCMT and the NRAO 12m telescopes sample approximately the same gas and therefore $r_{21}(^{13}\text{CO}) = 1.7$. The results are shown in Table 3.6.

In Table 3.6 it is shown that the line ratios of NGC 5135 as well as the ones of the “average” starburst can be reproduced fairly well by a single gas phase. Figure 3.5 illustrates the contour map of $\log \chi$ overlaid in the $(n(\text{H}_2), \Lambda)$ parameter space for NGC 5135 for the temperature that gives the best fit.

In the case of Arp 220 we did not find a good fit for $r_{21} = 0.53$ and $r_{21}(^{13}\text{CO}) > 1$. Nevertheless we must mention that this lower limit reported by Casoli et al. (1992) may not be reliable. We find $R_{21} = 18$ (see Table 3.3) which is in perfect agreement with their value. However the value $r_{21} = 0.53$ deduced from our measurements and data taken from the literature (see Table 3.1) is lower than their reported value of $r_{21} = 0.7$. In order for $r_{21}(^{13}\text{CO}) > 1$ it has to be $R_{10} = (r_{21}(^{13}\text{CO})/r_{21}) R_{21} > 34$ which is plausible but it hasn’t been measured yet.

It is also interesting to note that for $r_{21} \approx 0.8 - 1.0$, the parameter space of $(T_{\text{kin}}, n(\text{H}_2), \Lambda)$ for which it is $R_{10} = 10 - 15$ and $1 < r_{21}(^{13}\text{CO}) \leq 1.5$ can be found within the regime of superthermally excited $^{13}$CO $J=1-0$ where $T_{\text{ex}}(1-0)/T_{\text{kin}} > 1$. This particular feature of the CO $J=1-0$ transition has been noticed by Goldsmith (1972), De Jong et al. (1975) and Leung & Liszt (1976) and it occurs because collisional excitations from $J=0$ to $J=2$ occur at a comparable rate to those from $J=0$ to $J=1$, while spontaneous radiative decays are faster for $J=2-1$ than for $J=1-0$ ($A_{21}/A_{10} \approx 10$). As a result, the $J=1$ level may become overpopulated. The effect tends to be quenched at high optical depths where radiative trapping sets in and thermalizes the levels. For this reason it is the rare CO isotopes that are expected to be superthermally excited rather than $^{12}$CO. Generally the conditions needed for the $J=1-0$ line to be superthermal can be found in the regime where a) $T_{\text{kin}} \geq 20$ K, b) $n(\text{H}_2) \geq 2 \times 10^3$ cm$^{-3}$, and c) $\tau \leq 0.1$ (Leung & Liszt 1976).
### Table 3.6 NGC 5135, average starburst: LVG model results

| Galaxy          | $r_{21}, r_{21}(^{13}\text{CO}), R_{10}$ | $\sqrt{r_{21}, r_{21}(^{13}\text{CO}), R_{10}}$ | $\left( T_{\text{kin}}, \nu(\text{H}_2), \Lambda \right)$ | $T_{10}$ | $\frac{T_{\text{ex}}}{T_{\text{kin}}}$ | $\chi_{\text{min}}$ |
|-----------------|------------------------------------------|-----------------------------------------------|---------------------------------|----------|---------------------------------|----------------|---|
| NGC 5135        | 0.85, 1.70, 26                           | [0.99, 1.60, 23]                               | (20, 10, 1)                     | 1.7      | 1.46                            | 1.4           |
| Average starburst| 0.90, 1.30, 10                           | [0.90, 1.11, 10]                               | (27, 3, 10)                     | 3.6      | 1.36                            | 0.53          |
| Average starburst| 0.90, 1.30, 15                           | [0.86, 1.16, 15]                               | (14, 10, 1)                     | 3.1      | 1.20                            | 0.44          |

Note: The grid of the LVG models and the fitting procedure is the same as in Table 3.5 except for the temperature range where $T_{\text{kin}} = 8 \rightarrow 65$ K with $\Delta T_{\text{kin}} = 2$ K.

- a The observed line ratios.
- b The $(T_{\text{kin}}, \nu(\text{H}_2), \Lambda)$ parameters (units as in Table 3.5) that give the best fit.
- c The optical depth of the $^{12}\text{CO}$ J=1–0 transition.
- d $T_{\text{ex}}$ is the excitation temperature of the $^{13}\text{CO}$ J=1–0 transition.
- e The line ratios estimated from the LVG model with the smallest $\chi$. 

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Figure 3.5: Contour map of log$\chi$ with $T_{\text{kin}} = 20$ K for NGC 5135. The minimum value is $\log \chi_{\text{min}} = 0.14$, the contour spacing is $\Delta \log \chi = 0.2$ and $n(\text{H}_2)$, $\Lambda$ are expressed in logarithmic scale in units of cm$^{-3}$ and (km s$^{-1}$ pc$^{-1}$)$^{-1}$ respectively.
Moreover, the larger the kinetic temperature of the clouds the wider the density range over which superthermality of the J=1–0 transition can occur, for example for $T_{\text{kin}} = 60$ K, $A \sim 10^{-5}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$ this range is $n$(H$_2$) $\sim 10^3 - 10^5$ cm$^{-3}$. Such conditions are plausible for the molecular gas in the inner 1 kpc of a luminous starburst and as we will see in the case of NGC 1068, a superthermal excitation of the $^{13}$CO J=1–0 line may be occurring in the diffuse and warm gas phase that characterizes the outer parts of the “average” molecular cloud.

Thus we conclude that the average line ratios $R_{10} = 10 - 15$, $r_{21}(^{13}$CO) = 1.3 and $r_{21} = 0.9$ found for the nuclear regions (L $\leq$ 1 kpc) of Seyfert and/or starburst galaxies can be accounted for by a single, relatively warm ($T_{\text{kin}} \geq 20$ K) gas phase. A two-component gas model, while obviously not excluded, becomes necessary only for $r_{21} \leq 0.6$. Probing the conditions in the star-forming circumnuclear regions of Seyfert and starburst galaxies in more detail requires estimates of additional line ratios like $^{12}$CO, $^{13}$CO (3–2)/(1–0). Multiple transitions of dense gas tracers like CS, HCN and HCO$^+$ can help separate the properties of any distinct gas phases that may be present in these regions. Finally, in order to avoid “averaging-in” colder molecular gas from the disk, all the aforementioned measurements have to be conducted at a high enough resolution that only the warm nuclear gas is sampled. In the next two chapters we will analyze the conditions of the molecular gas in the luminous Sy2/starburst galaxy NGC 1068 in a more detailed fashion than in the Seyferts observed in our survey. For this galaxy we fully mapped the transitions J=3–2, J=2–1 for $^{12}$CO and $^{13}$CO and obtained an interferometric map of the J=1–0 transition for the significantly less abundant isotope C$^{18}$O as well as two test spectra of C$^{18}$O J=2–1. These additional observations with their higher angular resolution allow us to study only the warm nuclear gas of NGC 1068 and test the hypothesis about a two-component gas much more rigorously.
3.5.1 Molecular gas estimates for warm and cold gas

The presence of a global gradient of molecular gas properties can in principle affect the total gas mass estimate $M(H_2)$ from the $^{12}$CO $J=1-0$ luminosity $L_{CO}$ using the empirical galactic conversion factor $X_G = M(H_2)/L_{CO} \approx 5 \ M_\odot (K \ km \ s^{-1} \ pc^2)^{-1}$ (Solomon & Barrett 1991). The reason is that $X$ depends on the average $H_2$ density $n$ and the brightness temperature $T_b$ of the $^{12}$CO $J=1-0$ transition. For virialized molecular clouds and optically thick $^{12}$CO emission, this dependency can be simply expressed as $X = 2.1 \sqrt{n}/T_b$ (e.g., Maloney & Black 1988, but see also Bryant & Scoville 1996 for a recent detailed analysis), which for Galactic molecular clouds results in the aforementioned empirical value. From the LVG solutions for the warm gas in an average starburst (Table 3.6), we find that the use of the standard galactic conversion factor may underestimate $M(H_2)$ by no more than a factor of $\sim 3$. On the other hand, other factors like high pressure confinement of the molecular clouds (e.g., Bryant & Scoville 1996), heating by an enhanced cosmic ray density (Allen 1996) may result in a significant overestimate of gas mass when $X_G$ is used. Indeed, this seems to be the case in our more detailed study of the molecular gas in NGC 1068 (Chapters 4, 5) we find that the “differentiation” of the molecular gas in two distinct gas phases, with one of them being not virialized and the other one optically thick and dense.

The discrepancy can also be serious for cold and relatively dense gas. In the case of IC 5135 our LVG analysis indicates $X \approx 32$ and hence the standard galactic conversion factor can underestimate the mass of the cold gas by a factor of $\approx 7$. This factor could be even larger for lower kinetic temperatures (e.g., Allen & Lequeux 1993; Loinard et al. 1995) and lower metallicities associated with less processed gas at large galactocentric radii.
3.6 Conclusions from the survey

We have conducted a survey of the $^{12}\text{CO}$, $^{13}\text{CO}$ J=1-0, J=2-1 lines for a sample of Seyfert galaxies in order to probe properties of their global molecular gas reservoir. The main conclusions of our study are as follows:

1. We find that the average value of $\langle r_{21} \rangle = 0.71$ ratio for Seyfert galaxies as a class is smaller than $\langle r_{21} \rangle = 0.9$ found for the centers of nearby spirals and starbursts. A comparison of Seyferts to a large sample of galaxies with various degrees of nuclear activity like LINERs, starbursts and quiescent spirals reveals that especially in the case of Seyfert and starburst galaxies there is a correlation between $r_{12}$ and the ratio of the source size $\Omega_s$ to the beam size $\Omega_{mb}$. In this correlation it seems that the low $r_{21}$ line ratios are associated with small values of $\Omega_s/\Omega_{mb}$.

2. This correlation could be due to the presence of a global gas excitation gradient where warm ($T_{\text{kin}} \geq 20$ K) gas lies preferentially in the central parts of the galaxy while a population of cold ($T_{\text{kin}} < 10$ K) optically thick molecular clouds dominates the emission at large galactocentric distances. In Seyfert and starburst galaxies, the frequent presence of intense nuclear ($\leq 1$ kpc) star formation can readily establish such an excitation pattern.

3. We find that $\langle R_{10} \rangle = 12$ and $\langle R_{21} \rangle = 13$ irrespective of Seyfert type. These ratios are similar to the ones found for nearby spirals and starburst galaxies. High ($R>15$) values are measured towards merging/interacting galaxies. We also find that low $R_{10} \leq 8$ ratios seem to be mainly associated with low values $r_{21} \leq 0.7$ which characterize a cold, optically thick and possibly subthermally excited gas phase that seems to dominate the extended CO emission. For this gas component there are indications that the application of the standard galactic conversion factor of CO luminosity to $\text{H}_2$ mass may significantly underestimate the amount of molecular gas present.

4. We used a Large Velocity Gradient (LVG) code to model the conditions of the molecular gas in a few specific examples of Seyfert galaxies whose CO emission was found to be dominated by either the cold and very likely extended gas component or
by the warm nuclear gas. In the case of IC 5135, an IR-luminous Sy2/starburst galaxy, the gas over scales of ~6 kpc seems to be cold ($T_{\text{kin}} < 10$ K) and subthermally excited, while the inner 1 kpc of the archetypal Sy2/starburst galaxy NGC 1068 is warmer ($T_{\text{kin}} \geq 20$ K). Moreover we conclude that $R_{10} = 10 - 15$ and $1 < r_{21}(^{13}\text{CO}) \leq 1.5$ that are frequently measured towards the centers of Seyfert and starburst galaxies do not necessarily imply a two-component molecular cloud ensemble, as it has been proposed in previous studies, unless $r_{21} \leq 0.6$. 
Chapter 4

NGC 1068: Observations and Data reduction

4.1 An overview

The galaxy NGC 1068 is considered the archetypal Seyfert 2 galaxy and, being a prominent member in Carl Seyfert’s original list of such galaxies, it was one of the first ones to be studied extensively. It is also the best studied example of a close hybrid starburst/Sy2 galaxy and thus an object of great importance in the study of the links between AGN and starburst activity.

The large bolometric luminosity of this source is almost equally divided between an unresolved AGN and a circumnuclear starburst (Telesco et al. 1984). High resolution $^{12}$CO J=1–0 maps of this galaxy (Planesas, Scoville & Myers 1991; Helfer & Blitz 1995) have revealed a rich structure of Giant Molecular gas Associations (GMAs) with high brightness temperature. The most detailed map is the one presented by Helfer & Blitz (1995) since it deals effectively with the “missing-spacings” problem that is associated with interferometer maps (see the appendix of Wilner & Welch 1994) by including single dish data. Their map shows the molecular gas bar present in the inner $\sim 30''$ of this galaxy, in good agreement with the 2.2$\mu$m stellar bar imaged by Scoville et al (1988) and Thronson et al. (1989) and which has not been detected in previous interferometric maps (e.g., Planesas, Scoville & Myers 1991). Moreover the
Helfer & Blitz map allows them to study the kinematics of the molecular gas in detail and their HCN(1–0) map reveals the location of the dense molecular gas, which is found to be concentrated mainly in the inner ~ 350 pc of the nucleus. This dense gas concentration is probably associated with the dense molecular gas torus that hides the AGN and its associated BLR (Antonucci & Miller 1985) from view.

As we mentioned in the introduction, Maiolino et al. (1995), (1997) find that Sy2 are on average much more IR-luminous than Sy1 or field spirals but they do not seem to have any “excess” molecular gas. If one considers FIR luminosity as a measure of star formation rate, then the above picture suggests that Sy2’s are more efficient star formers than Sy1’s and field spirals since, for the same amount of molecular gas, they seem to have higher star formation rates. If such a scenario is correct, it points towards a link between phenomena that occur on vastly different spatial scales, namely the efficiency of a circumnuclear starburst in forming stars over a scale of L ≥ 1 kpc and the obscuring torus with L ~ 1 – 10 pc whose orientation is the cause for the difference between type 1 and type 2 Seyfert nuclei.

For the statistical purposes of their study Maiolino et al. (1997) have used the standard galactic conversion factor X to deduce H2 mass from 12CO J=1–0 luminosity. However, previous studies of M 82 (Wild et al. 1992), IC 342 (Eckart et al. 1990) have demonstrated that 12CO luminosity may not be a very reliable molecular gas mass tracer in starburst environments. Also, statistical studies of starburst galaxies by Aalto et al. (1995) suggest that a two-component gas phase may be present in the nuclei of starbursts. One of these two components may be optically thin (12CO J=1–0 has τ10(12) ~ 1) and most importantly it may consist of non self-gravitating clouds. In such a case the line width of the 12CO lines originates from intense turbulent kinematic fields. This possibility together with the expected higher kinetic temperatures of molecular clouds in a starburst environment may render the application of the standard galactic conversion factor X unreliable. This is because if such types of clouds are dominant in starburst nuclei then neither the line width nor the brightness of 12CO necessarily reflect the total mass of H2 and LCO may actually overestimate the amount of molecular gas present.
These reasons necessitate a detailed study of the molecular gas in the hosts in Seyfert nuclei in order to investigate the physical conditions of the molecular gas and the possible effects of an intense star forming environment. Since it is mostly Sy2's that exhibit these intense starbursts it follows that such a study is urgently needed for the hosts of type 2 Seyfert nuclei.

4.1.1 NGC 1068 as a starburst

Evidence for a very luminous circumnuclear starburst in NGC 1068 is abundant. A recent Hα survey of 55 Seyferts and low-ionization nuclear emission line regions (LINERs) by Delgado et al. (1997) reveals NGC 1068 to have the highest Hα luminosity in the sample. Their Hα map shows that this emission is arranged in luminous Hα knots in the inner 30″ that are closely associated with the GMAs seen in 12CO J=1–0 interferometer maps. Another indicator of star forming activity, the FIR luminosity of the extended region of NGC 1068, is $L_{\text{FIR}} \sim 1.5 \times 10^{11} \, L_\odot$ (Telesco et al. 1984), making this galaxy four times more luminous than M 82.

The prominent position of NGC 1068 as the archetypal Sy2/starburst galaxy and its relative proximity make it the galaxy of our choice for a multi-line millimeter spectroscopic study of its circumnuclear starburst region at a high angular resolution. The observational parameters adopted for NGC 1068 and other relevant information are displayed in Table 4.1 presented below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{1950}^a$</td>
<td>$2^h , 40^m , 07.08''$</td>
</tr>
<tr>
<td>$\delta_{1950}^a$</td>
<td>$-00^\circ , 13' , 31.45''$</td>
</tr>
<tr>
<td>$V_{\text{LSR}}^b$</td>
<td>1125 km s$^{-1}$</td>
</tr>
<tr>
<td>Distance$^c$</td>
<td>14 Mpc</td>
</tr>
<tr>
<td>Linear size equivalent to 1&quot;</td>
<td>68 pc</td>
</tr>
<tr>
<td>$L_{\text{FIR}}^d$</td>
<td>$1.5 \times 10^{11} , L_\odot$</td>
</tr>
<tr>
<td>M(H$_2$) from single dish data$^e$</td>
<td>$1.5 \times 10^{10} , M_\odot$</td>
</tr>
</tbody>
</table>

$^a$ Optical nucleus position; Clements (1981).
$^d$ (excluding AGN) Telesco et al. (1984).
$^e$ Planesas, Scoville & Myers (1991) and references therein.
4.2 The OVRO interferometric measurements

We used the five-element millimeter interferometer of the Owens Valley Radio Observatory (OVRO) during the periods of 1993 December to 1994 May and 1995 January to obtain maps of NGC 1068 in the $^{13}$CO and $^{18}$O $J=1-0$ transitions. The line frequencies are below 112 GHz where the OVRO mixers can operate single sideband (SSB) thus giving high sensitivity ($T_{\text{SSB}}=200-300$ K). We have observed the two lines simultaneously at a frequency resolution of $\Delta \nu_{\text{chan}}=4$ MHz (11 km s$^{-1}$) with a total of 56 channels for each transition. Amplitude and phase calibration was achieved by observing 0106+013 and 0221+067 every 20 minutes. The planets Uranus and Mars and the quasi-stellar object 3C 454.3 were used to calibrate the flux density scale with an uncertainty of $\beta \approx 10\%$. The u-v coverage of our tracks was 8 – 80 $k\lambda$ yielding nearly identical synthesized beams for the $^{13}$CO and $^{18}$O observations.

The AIPS task "MX" was utilized to map and deconvolve the dirty beam from the brightness distribution. The deconvolution procedure is not straightforward since the molecular ring of NGC 1068 couples strongly to the first two sidelobes of the dirty beam which have high response levels, a direct result of the equatorial location of this galaxy. Thus, extra caution was required to ensure reliable maps. We inspected the "dirty" channel maps individually to locate the various emitting regions, and then we employed various deconvolution schemes that resulted in similar CLEANed brightness distributions in every channel. We then compared both the channel-to-channel as well as the velocity-integrated $^{13}$CO emission with the $^{12}$CO $J=1-0$ interferometer maps by Planesas, Scoville & Myers (1991) and the latest one by Helfer & Blitz (1995) and we find very good agreement of the observed distribution of the emission. As expected, because of the weakness of the $^{13}$CO relative to the more abundant $^{12}$CO and because single dish data are not included, we do not detect any trace of the molecular bar seen in the map of Helfer & Blitz (1995). A comparison of our $^{13}$CO $J=1-0$ integrated emission map to another, high sensitivity map obtained with the IRAM millimeter interferometer (Tacconi 1995) for the same transition reveals excellent agreement between the two except in the regions of the molecular bar.

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The good agreement with the maps found in the literature indicates a successful removal of all the beam artifacts from our $^{13}$CO $J=1-0$ data set. We then applied the same deconvolution to obtain the maps of the much weaker $^{18}$O $J=1-0$ isotope. The resulting (untapered) naturally weighted $^{13}$CO and $^{18}$O channel maps have a resolution of 4.6'' x 4.2'' and rms noise of $\sigma_{\text{ch}}=8$ mJy beam$^{-1}$, estimated in a line-free channel.

If $\sigma_{\text{ch}}$ is the thermal (rms) noise in every channel map, then the uncertainty of the integrated line flux $S$ (Jy km s$^{-1}$) can be expressed as follows

$$\sigma(S) = [N_{\text{ch}}N_b\sigma_{\text{ch}}^2 + (\beta S)^2]^{1/2}$$  \hspace{1cm} (4.1)

where $N_{\text{ch}}$ is the number of channels and $N_b$ the number of synthesized beams used to find $S(^{13}$CO). The factor $\beta \approx 0.1$ represents the 10% uncertainty in the absolute flux calibration. For $N_b = 1$ the last equation gives the error of the velocity-integrated line brightness $I$ (Jy/beam km s$^{-1}$) for every point in the map, while for $N_{\text{ch}} = 1$ it gives the error in individual channel maps. The $I(^{13}$CO) map is shown in Figure 4.1 and it has been corrected for primary beam attenuation by assuming a gaussian primary beam with FWHP=70''. We find $S(^{13}$CO) = 89 $\pm$ 9 Jy km s$^{-1}$ and an area-averaged ratio $R_{10} = ^{12}$CO/$^{13}$CO = 14 $\pm$ 2 from our $^{13}$CO OVRO map and the $^{12}$CO map (also done with OVRO) by Planesas, Scoville & Myers (1991). This value of $R_{10}$ is in excellent agreement with the value of $R_{10}$ found by Young & Sanders (1986) which used the wide beam (45'') of the 14m FCRAO telescope to observe the circumnuclear region of NGC 1068. It is also in the same range of values measured in the bulges and disks of other nearby galaxies (Rickard & Blitz 1985; Young & Sanders 1986; Sage & Isbell 1991), or circumnuclear regions of active galaxies (Aalto et al. 1995, this study).

Our high resolution $^{13}$CO $J=1-0$ measurements give us an opportunity to estimate the molecular gas surface density along the line of sight over small scales ($\sim 300$ pc) by assuming LTE and an optically thin $^{13}$CO $J=1-0$ emission. In this case the beam-averaged column density of $^{13}$CO can be expressed as follows:
where \( \tau_{13}(V) \) is the beam averaged optical depth of \(^{13}\text{CO} \) as a function of velocity (km s\(^{-1} \)). The observed beam-averaged \(^{13}\text{CO} \) brightness temperature is given by

\[
T_b^{(13\text{CO})} = \left( \frac{5.28}{e^{5.28/T_{\text{kin}}} - 1} - \frac{5.28}{e^{5.28/T_{\text{emb}}}} \right) \int_{\text{beam}} \left[ 1 - e^{-\tau_{13}(V,\Omega)} \right] d\Omega.
\] (4.3)

Omitting the cosmic microwave background term causes an error of less than 10\% for the warm clouds (Planesas et al. 1991)) in NGC 1068. Hence, assuming an abundance of \([^{12}\text{H}/^{13}\text{CO}] \approx 4 \times 10^5\), and \( \tau_{13}(V) \ll 1 \), equations 4.2 and 4.3 give

\[
N(H_2) = 9.7 \times 10^{19} \left( \frac{T_{\text{kin}}}{5.28} \right) e^{5.28/T_{\text{kin}}} \int_{\text{line}} T_b^{(13\text{CO})} dV \text{ cm}^{-2}.
\] (4.4)

In the case of a significant \(^{13}\text{CO} \) optical depth, Equation will underestimate the true column density. The brightness temperature of \(^{12}\text{CO} \) J=1–0 of the GMAs of NGC 1068 is particularly high \((T_b \sim 10 \text{ K})\) over scales of 200 pc when compared with the one observed for the Milky Way over similar linear scales (Planesas, Scoville & Myers 1991). Assuming a temperature of \( T_{\text{kin}} = 20 \text{ K} \), which is equal to the average dust temperature estimated for the same region using mm/sub-mm measurements (Thronson et al. 1987) yields \( \lambda(T_{\text{kin}}) = (T_{\text{kin}}/5.28)e^{5.28/T_{\text{kin}}} \approx 5 \). Substituting this value into Equation 4.4 and converting this to gas mass surface density \( \Sigma(H_2) \), gives

\[
\Sigma(H_2) = 1.0 \Omega_b^{-1} \int_{\text{line}} S_\nu^{(13\text{CO})} dV \ M_\odot \text{ pc}^{-2},
\] (4.5)

where \( S_\nu^{(13\text{CO})} \) is the flux density in mJy per synthesized beam and \( \Omega_b = 1.13\theta_x'' \theta_y'' \) is the beam area.

A map of the integrated line brightness of \(^{13}\text{CO} \) J=1–0 and the corresponding gas mass surface density estimated from Equation (4.5) is shown in Figure 4.1. The range of \( \Sigma(H_2) \) estimated from the the standard galactic conversion factor \( X_G = 5 (\text{K km s}^{-1} \text{ pc}^2)^{-1} M_\odot \) (cf Solomon & Barret 1991) and the observed brightness of
$^{12}$CO $J=1-0$ in a published OVRO map with similar resolution (Planesas, Scoville & Myers 1991) is $\Sigma_{G}(H_{2}) = 490 - 1810\ M_{\odot}\ pc^{-2}$. This range is $\approx 4$ times higher than the one estimated from the $^{13}$CO $J=1-0$ brightness under the assumption of LTE.

This may be due to a combination of factors that can affect both methods that we used for estimating the molecular gas mass. A diffuse non-virialized gas component may be dominating the $^{12}$CO emission and thus making its integrated line brightness overestimate the gas mass present. Such a component may indeed be prominent in starburst environments as suggested by the comprehensive study of the molecular gas in such environments by Aalto et al. (1995). On the other hand if a significant amount of mass is "locked" in a gas phase for which $^{13}$CO $J=1-0$ has $\tau > 1$, then equation 4.4 will underestimate the true $\Sigma(H_{2})$. In the following section as well as in Chapter 5 we present evidence that strongly suggests the presence of at least two gas phases in the circumnuclear region of NGC 1068 with exactly the aforementioned characteristics.
Figure 4.1: Contour map: Integrated intensity $I({}^{13}\text{CO})$ (Jy/beam km s$^{-1}$) at a resolution of 4.6" $\times$ 4.2". The rms thermal noise is $\sigma = 0.6$ Jy/beam km s$^{-1}$. The contours are (4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15)$\times\sigma$, and the HPBW of the restoring beam is shown in the bottom left corner. Gray-scale map: Molecular gas surface density $\Sigma(\text{H}_2) \sim 110 - 410$ $M_\odot$ pc$^{-2}$ estimated from Equation 4.5.
4.2.1 The $^{13}$CO, $^{18}$O J=1–0 maps

We tapered our $^{13}$CO and $^{18}$O maps over the same u-v range which yields almost identical synthesized beams and averaged two channels in order to increase the S/N ratio. Emission from C$^{18}$O was detected in all channels in which significant $^{13}$CO emission is found. More specifically, we have detected C$^{18}$O in 21 locations in the molecular arms of NGC 1068 at a 4-8σ level, with nine of them at the southern molecular arm. The two sets of channel maps of $^{13}$CO and C$^{18}$O can be seen in Figures 4.2 and 4.3 respectively.

We estimated the ratio $R_{10}^{(18)} = S_{\nu}(^{18}$O)/$S_{\nu}(^{13}$CO) in 26 regions in which significant (S/N>3) $^{13}$CO is detected. This is the case in 16 out of the 20 channel maps (see Figure 4.3). The C$^{18}$O is detected in 21 (~80%) of these regions. The flux densities of the various emission features were calculated by using the AIPS task IMEAN to find $S_{\nu}$ within a box placed around every feature. The $^{13}$CO maps were used to define the appropriate rectangular boxes that contain all the emission and the same ones were used to evaluate the C$^{18}$O flux density. Since $^{13}$CO and C$^{18}$O are observed simultaneously their ratio does not depend on the absolute calibration scale factor and only the thermal rms factor in Equation 4.1 contributes to the error of $R_{10}^{(18)}$. The transition 5$_{05}$ – 4$_{04}$ of HNCO has a rest frequency close (~123 MHz higher) to the frequency of C$^{18}$O, and it could in principle contribute to the C$^{18}$O emission in some channel maps (Henkel, Whiteoak, & Mauersberger 1994). In our case, this is very unlikely, since the observed C$^{18}$O emission has a FWZI~105 MHz, which is smaller than the separation $\delta \nu = 123$ MHz between the two lines.

The measured values of $R_{10}^{(18)}$ among the various GMAs have a mean value $\langle R_{10}^{(18)} \rangle = 0.30 \pm 0.10$. If we estimate this ratio over whole images rather than individual GMAs we find $\langle R_{10}^{(18)} \rangle = 0.32 \pm 0.10$. The full range of values measured is $0.10 \pm 0.05 \leq R_{10}^{(18)} \leq 0.67 \pm 0.22$, but in most regions (~75%) we find $R_{10}^{(18)} > 0.20$. In a few channels (e.g., V=1070 km s$^{-1}$) a rather large difference ($\Delta R_{10}^{(18)} \sim 0.5$) is observed between the values of $R_{10}^{(18)}$ measured in the north and the south part of the CO emission. Similar variations are also found among individual channels.
Figure 4.2: Tapered channel maps of $^{13}$CO (mJy beam$^{-1}$) at a spatial resolution of $5.77'' \times 4.11''$ and frequency resolution of $\Delta \nu_{\text{ch}} = 2 \times 4$ MHz. The rms noise is $\sigma = 5$ mJy beam$^{-1}$. The contours are $(-4, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22) \times 5$ mJy beam$^{-1}$ and the HPBW of the restoring beam is shown at the bottom left of channel $V = 940$ km s$^{-1}$. 
Figure 4.3: Tapered channel maps of C^{18}O (mJy beam$^{-1}$) at a spatial resolution of 6.27'' × 4.24'' and frequency resolution of $\Delta\nu_{ch} = 2 \times 4$ MHz. The rms noise is $\sigma = 5$ mJy beam$^{-1}$. The contours are (−4, −3, 3, 4, 5, 6, 7, 8, 9)× 5 mJy beam$^{-1}$ and the HPBW of the restoring beam is shown at the bottom left of channel $V=940$ km s$^{-1}$. 
4.2.2 Preliminary evidence for a two-component gas

Our high resolution $^{13}$CO, $^{18}$O J=1–0 maps in Figures 4.2, 4.3 demonstrate that the $^{18}$O emission doesn’t smoothly trace the $^{13}$CO across the various GMAs and can vary drastically from one location to the next with values of $R_{10}^{(18)}$ as high as $\sim 0.65$. For optically thin $^{13}$CO, $^{18}$O emission, $R_{10}^{(18)}$ reflects the relative abundance ratio $[^{18}$O/$^{13}$CO] which then is significantly higher than $[^{18}$O/$^{13}$CO] = 0.12 – 0.14 inferred for the Milky Way from $^{12}$CO, $^{13}$CO and $^{18}$O observations (e.g., Wannier 1980; Henkel & Mauersberger 1993; Langer & Penzias 1993). High values of $R_{10}^{(18)}$ have been detected towards other starburst nuclei with high FIR luminosity like NGC 3256, NGC 253, IC 342, M82 and NGC 4945 (Sage, Mauersberger, & Henkel 1991; Casoli, Dupraz, & Combes 1992; Henkel & Maursberger 1993), where $R_{10}^{(18)} \sim 0.25 – 0.30$.

While it is possible that an enhancement of $[^{18}$O/$^{13}$CO] that can occur in starburst nuclei (Henkel & Mauersberger 1993) may play a role in the observed high values of $R_{10}^{(18)}$ it is very unlikely that it can be solely responsible for values as high as the ones observed in individual GMAs in NGC 1068. Moreover it is also hard to attribute the observed large spatial variations of the $^{18}$O/$^{13}$CO intensity ratio over scales of $\sim 400$ pc to variations of abundance alone. This is because the mixing of interstellar gas is expected to be effective enough to homogenize the isotope ratios over similar or larger scales, even during an ongoing burst of star formation (Henkel & Mauersberger 1993).

It seems more likely that the optical depth of $^{13}$CO J=1–0 is not negligible; hence a large, varying $\tau$ of this isotope among the various GMAs could be responsible for the large values of $R_{10}^{(18)}$ and its spatial variations. If one gas phase dominates the emission

$$ R_{10}^{(18)} = \frac{1 - e^{-[r]\tau}}{1 - e^{-\tau}} \quad (4.6) $$

where $[r] = [^{18}$O/$^{13}$CO] and $\tau$ is the optical depth of the $^{13}$CO J=1–0 transition. Assuming an abundance ratio of $[r] = 0.12$, then for $R_{10}^{(18)} \geq 0.20$ the previous equation yields $\tau > 1.5$. For such a large $^{13}$CO optical depth the implied ratio of $^{12}$CO/$^{13}$CO for J=1–0 is $R_{10} \sim 1$. This is an order of magnitude smaller than any value measured.
for this ratio towards either isolated GMAs (Papadopoulos, Seaquist & Scoville 1996) or globally for this particular galaxy or more quiescent spirals (e.g., Young & Sanders 1986). Hence it seems that \(^{12}\text{CO},\ ^{13}\text{CO}\) and \(^{18}\text{O}\) cannot all be tracing the same molecular gas phase, a suggestion that we explore in Chapter 5.

### 4.3 The JCMT observations

#### 4.3.1 The \(^{12}\text{CO},\ ^{13}\text{CO}\) J=2–1 measurements

We used receiver A2 on the James Clerk Maxwell Telescope (JCMT)\(^1\) in two observing runs between 1994 January 2 and 1994 January 8, and between 1994 November 26 and 1994 November 29 to observe NGC 1068 to make maps of the emission lines \(^{12}\text{CO},\ ^{13}\text{CO}\) J=2–1 lines at 230.538 GHz and 220.398 GHz respectively. The DAS (Dutch Autocorrelation Spectrometer) was employed as a backend with a total usable bandwidth of \(\sim 700\) MHz, corresponding to velocity coverage of \(\sim 900\) km s\(^{-1}\) at a spectral resolution of 0.625 MHz. The map center and the \(V_{\text{LSR}}\) are listed in Table 4.1. The area mapped was along a rotated grid with PA = 40° (for more efficient mapping of the CO emission) and sampling was at half beamwidth interval. The grid-cell is an equilateral triangle with a size of \(\Delta\theta_c = 10''\), which provides the optimum coverage of the circumnuclear emitting region of NGC 1068 at a Nyquist sampling.

This type of grid is uniquely determined by the demand of having a) a uniform sampling pattern and b) every sampled point having the maximum number (N=6) of closest neighboring points at a distance of \(\delta\theta = \Delta\theta_c\).

The map size was \(\sim 100'' \times 60''\) (N=85 points) for \(^{12}\text{CO}\) and \(\sim 80'' \times 60''\) (N=57 points) for \(^{13}\text{CO}\). For the \(^{12}\text{CO}\) line the integration time per point was \(t_{\text{int}} = 1 - 2\) mins and typical system temperatures across the map were \(T_{\text{sys}} \sim 350 - 450\) K. For the \(^{13}\text{CO}\) line these figures are: \(t_{\text{int}} = 10 - 20\) mins and \(T_{\text{sys}} \sim 400 - 500\) K. Focus and pointing were monitored frequently by observing bright quasars and planets and

\(^1\)The JCMT is operated by the Observatories on behalf of the UK Particle Physics and Astronomy Research Council, the Netherlands Organization for Scientific Research and the Canadian National Research Council.
the pointing (rms) error was found to be $\sim 4''$. We performed all observations using a beam switching mode with a beam throw of 150$''$ in azimuth and at the recommended rate of 1 Hz.

The profile of the main beam of the telescope at these frequencies is closely approximated by a gaussian beam with HPBW=21$''$. We converted the $T_A^*$ temperature scale of the JCMT spectra to the $T_{mb}$ scale by using the relation $T_{mb} = T_{A}^*/n_{mb}$, adopting a beam efficiency of $n_{mb} = 0.69$ (Matthews 1996). The error associated with the line intensity measurements was estimated using the relation 2.1. The calibration uncertainty (the $r_{rms}$ factor in equation 2.1) was found to be $\sim 0.15$ for both frequencies, while the systematic factor is $\sim 0.10$ (Goeran Sandell, private communication). We performed an additional check on the overall uncertainty of the line intensities by frequently monitoring some standard points on our map. The measured dispersion of the associated line intensities is perfectly consistent with the rms uncertainty estimated from the first two terms of equation 2.1 and very good agreement was found for the line profiles. Planesas et al. (1989) used the IRAM 30m telescope to map the $^{12}$CO J=1–0, 2–1 lines in NGC 1068 with a resolution of $\sim 22''$. We find reasonably good agreement with the profiles of the spectra they present for the nucleus and four off-center positions.

The grid spectra of $^{12}$CO, $^{13}$CO J=2–1, after subtracting a linear baseline and smoothing them to a velocity resolution of 8.13 km s$^{-1}$ (6.25 MHz), are shown in Figures 4.4 and 4.5.
Figure 4.4: The grid map of all the $^{12}$CO J=2–1 spectra. The temperature scale is $T_{mb} = -0.5...1.5$ K, the velocity range is $V_{LSR} = 850-1450$ km s$^{-1}$ and the resolution is $\Delta V_{chan} = 8.1$ km s$^{-1}$. 
Figure 4.5: The grid map of all the $^{13}$CO J=2–1 spectra. The temperature scale is $T_{mb} = -0.1...0.15$ K, the velocity range is $V_{LSR} = 850 - 1450$ km s$^{-1}$ and the resolution is $\Delta V_{chan} = 8.1$ km s$^{-1}$. 
4.3.2 The $^{12}$CO, $^{13}$CO J=3–2 measurements.

We used receiver B3i on JCMT in two observing runs between 1994 November 26 and 1994 November 29, and 1996 January 16 and 1996 January 18 to observe NGC 1068 and make a map of the emission line $^{12}$CO J=3–2 at 345.795 GHz. The DAS was again used and the usable bandwidth at 345 GHz corresponds to $\sim 600$ km s$^{-1}$ and the frequency resolution is 0.625 MHz. The map center, the LSR velocity and beam switching scheme are identical to the ones used for the J=2–1 observations. We made the map by using a grid identical to the one used for our $^{12}$CO, $^{13}$CO J=2–1 observations and a sampling interval of $\Delta\theta_c = 7''$. The map size is $\sim 80'' \times 60''$ (N=113 points). The integration time per point was $t_{\text{int}} = 2$ mins and typical system temperatures across the map were $T_{\text{sys}} = 750 - 1000$ K.

Focus and pointing were monitored frequently by observing bright quasars and planets and the pointing (rms) error was found to be $\sim 3''$. The beam shape at this frequency is closely approximated by a gaussian with HPBW=14''. A measurement of the main beam efficiency using Saturn was performed which yielded $n_{\text{mb}} = 0.53$, in good agreement with $n_{\text{mb}} = 0.58$ reported by Matthews (1996). In our conversion of the $T_A^*$ to the $T_{\text{mb}}$ scale we adopt the mean value $n_{\text{mb}} = 0.55$. The error of the line intensities was estimated by using Equations 2.1 and 2.2. The observations of bright spectral line standards yielded a calibration uncertainty of $\sim 0.10$ and the systematic error associated with the telescope efficiency factors is $\sim 0.10$ (Friberg, private communication).

Finally, we repeatedly monitored the spectral line emission of the map center throughout our runs and found excellent agreement among all the line profile measurements. The measured dispersion of the line intensities is consistent with what is expected from the first two rms terms in Equation 2.1. The grid spectra of $^{12}$CO J=3–2, after subtracting a linear baseline and smoothed to a resolution of 8.13 km s$^{-1}$ (9.375 MHz) are shown in figure 4.6.
Figure 4.6: The grid map of all the $^{12}$CO J=3–2 spectra. The temperature scale is $T_{mb} = -0.5...1.5$ K, the velocity range is $V_{LSR} = 850-1450$ km s$^{-1}$ and the resolution is $\Delta V_{chan} = 8.1$ km s$^{-1}$. 

We subsequently used the newly commissioned receiver B3 that replaced B3i in two further observing runs in 1997 November 27 to 1997 December 1, and 1997 December 27 to 1997 December 29 to obtain a fully sampled map of the $^{13}\text{CO} \ J=3-2$ transition at 330.588 GHz. The DAS bandwidth of the B3 receiver corresponds to $\sim 900 \text{ km s}^{-1}$ with a frequency resolution of $\Delta \nu_{ch} = 0.625 \text{ MHz}$. Receiver B3 is a new automated heterodyne receiver for the 345 GHz band, built at the National Research Council’s HIA in collaboration with SRON/University of Groeningen in Holland and CCLRC/RAL in the UK. It employs two low-noise Niobium SIS junctions which are normally used to simultaneously detect two orthogonal polarizations. A dual beam interferometer allows either single- or double-sideband operation. For the observations of the weak $^{13}\text{CO} \ J=3-2$ line we used the SSB mode in which the detectors look into a cold load at the image sideband frequency, which resulted in a dramatic improvement in sensitivity under most sky conditions. Typical system temperatures measured were of the order $T_{\text{sys}} \sim 500 \text{ K}$ and temperatures as low as $T_{\text{sys}} \sim 350 \text{ K}$ were obtained for significant parts of our run. By comparison, the old B3i receiver, at 330 GHz gave us typical $T_{\text{sys}} = 1100 - 1500 \text{ K}$. The commissioning of this receiver made the completion of the fully sampled $^{13}\text{CO} \ J=3-2$ map possible within reasonable time.

The integration time per point was $t_{\text{int}} = 10 - 15 \text{ mins}$ and we observed N=87 points. The grid spacing and orientation are identical to the ones used for the $^{12}\text{CO} \ J=3-2$ map. The beam switching scheme used for the $^{12}\text{CO}$, $^{13}\text{CO} \ J=2-1$ and $^{12}\text{CO} \ J=3-2$ observations was employed also for the $^{13}\text{CO} \ J=3-2$ observations. The pointing and focus were monitored by frequently observing the source OMC1 and planets, and the rms pointing offset was found to be $3'' - 4''$.

A measurement of $n_{mb}$ using Jupiter yielded $n_{mb} = 0.62$, in excellent agreement with $n_{mb} = 0.61$ found during the commissioning runs. The error of the line intensities was estimated by using Equations 2.1 and 2.2. The observations of several bright spectral line standards as well as OMC1 at $V_{\text{LSR}} = 1125 \text{ km s}^{-1}$ (many lines present) yielded a calibration uncertainty of $\sim 0.10$. The systematic error associated with the telescope efficiency factors is assumed to be $\sim 0.10$. The grid-spectra of $^{13}\text{CO} \ J=3-2$, after subtracting a linear baseline, are shown in Figure 4.7.
Figure 4.7: The grid map of all the $^{13}$CO J=3–2 spectra. The temperature scale is $T_{mb} = -0.1...0.1$ K and the velocity is $V_{LSR} = 850 - 1450 \text{ km s}^{-1}$. 
4.3.3 Two test spectra of $^{18}$O J=2–1

During one night of our 1997 November 27 to 1997 December 1 run poor weather at 330 GHz made it necessary to switch to receiver A2, with which we obtained two low-noise spectra of $^{18}$O J=2–1 at 219.560 GHz in two positions in NGC 1068. This allowed us to measure the ratio $R_{21}^{(18)} = C^{18}$O/$^{13}$CO J=2–1 and offers an independent check on the high values of the $R_{10}^{(18)}$ for J=1–0 that we have measured with OVRO. We employed beam switching at a frequency of 2 Hz and a beam-throw of 150" which resulted in remarkably flat and stable baselines, a prerequisite in the detection of such weak and broad spectral lines. The total integration time for the two points was $t_{\text{int}} = 1.5$ hrs and $t_{\text{int}} = 1.8$ hrs. The system temperatures measured were of the order of $T_{\text{sys}} \sim 500$ K.

Since it was important to obtain a reliable estimate of the absolute intensity of $^{18}$O J=2–1 we performed a measurement of the $n_{\text{mb}}$ of the telescope at the operating frequency of 219 GHz using Saturn. The value we measured is $n_{\text{mb}} = 0.70$, in excellent agreement with the value of $n_{\text{mb}} = 0.69$ reported in the JCMT observer's manual for this frequency regime. Moreover, during our long integrations we monitored the pointing and focus using Saturn and OMC1. Finally we performed an overall check of the calibration in a manner similar to the one we used for $^{13}$CO J=3–2, i.e., by monitoring the intensity of spectral lines in OMC1 that appear at $V_{\text{LSR}} = 1125$ km s$^{-1}$. The variations observed were within the calibration uncertainties observed for A2 at this frequency regime (see section 4.3.1). We present the two $^{18}$O J=2–1 spectra overlayed with the $^{13}$CO J=2–1 spectra from the corresponding positions in the next section.
4.4 The $^{12}$CO, $^{13}$CO maps

4.4.1 The $^{12}$CO $J=3-2$, 2–1, 1–0 maps

We performed an interpolation of the $^{12}$CO $J=3-2$, 2–1 grid maps by convolving them with a gaussian function with a FWHM $\theta_{G}$ slightly larger than the map sampling interval. This gives a robust interpolation while maintaining the original resolution of the map as much as possible. The resolution of the interpolated map is then found from $\theta_i = (\theta_{HPBW}^2 + \theta_{G}^2)^{1/2}$, where $\theta_{HPBW}$ is the resolution of the grid-map. For the $^{12}$CO $J=3-2$ map ($\theta_{HPBW} = 14''$) we used $\theta_{G} = 8''$ which gives $\theta_i(3-2) = 16''$, and for $^{12}$CO $J=2-1$ ($\theta_{HPBW} = 21''$) it is $\theta_{G} = 11''$ which gives $\theta_i(2-1) = 24''$. The cutoff size of the convolving gaussian was chosen to be $\theta_{cut} = 50''$ in both cases.

The $^{12}$CO $J=1-0$ map used in our analysis was obtained by Helfer & Blitz (1995) with the Berkeley-Illinois-Maryland Association (BIMA) interferometer and the NRAO 12m telescope. This map is the most suitable one for the purpose of comparison with our JCMT maps since its combination of interferometer and single dish measurements recovers all the CO flux. However low sensitivity and remnant phase errors make their $^{13}$CO $J=1-0$ BIMA/NRAO 12m map unsuitable for the purpose of detailed comparison with the $^{12}$CO $J=1-0$ emission. Hence we will use the high sensitivity $^{13}$CO $J=1-0$ map obtained with the OVRO millimeter interferometer (see Section 4.2). The BIMA map has been corrected for primary beam attenuation by assuming a gaussian profile with HPBW=100''.

We inserted the grid and the interpolated JCMT maps into the Astronomical Image Processing Software (AIPS) package where all the subsequent analysis was performed. The AIPS task HGEOM was employed to re-grid the JCMT maps in order to re-orient them in an (RA,DEC) grid and make them compatible with the interferometer maps. A check of the consistency of the interpolation and re-gridding of the JCMT maps was performed by comparing quantities like the area-averaged main beam brightness temperature $T_{mb}$ in individual channels, or the peak $T_{mb}$’s of the original discrete maps with the corresponding quantities in the final maps that we use in our analysis. We found good agreement within the thermal rms uncertainties.
We compared the interpolated $^{12}$CO $J=3-2$, $2-1$ maps with the $^{12}$CO $J=1-0$ BIMA map (convolved to the same spatial and frequency resolution) in all the velocity channels. We have also estimated the ratio of the area-averaged main beam brightnesses $r_{J+1} = T_{mb}(J + 1, J) / T_{mb}(1 - 0)$, $J=2, 1$ for every velocity channel. These maps and the corresponding line ratios are shown in Figures 4.8 and 4.9.

The close correspondence of the $^{12}$CO $J=3-2$, $J=2-1$ contour maps to the $^{12}$CO $J=1-0$ emission in every channel demonstrates that no serious pointing offsets are present in our JCMT maps. The emission from the higher transition $J=3-2$ seems to be less extended than the $J=1-0$ in most channels. This simply reflects the fact that significantly larger densities are needed to excite the $J=3-2$ transition to comparable brightness level as the $J=1-0$, and such conditions are usually found in smaller volumes in the molecular clouds where warm and dense gas is located.

The estimated channel-to-channel rms error of the $r_{32}$ and $r_{21}$ line ratios is of the order of 10%. This includes only the thermal rms error since the other two sources of error for the JCMT maps (see Appendix A) and the systematic calibration uncertainty in the flux conversion factor of the BIMA $^{12}$CO $J=1-0$ map are constant across the passband. The largest single source of error contributing to the total error of the $r_{32}$, $r_{21}$ line ratios is the $\sim 30\%$ flux calibration uncertainty of the $^{12}$CO $J=1-0$ BIMA map. Taking into account the other two sources of error associated with the JCMT measurements result to a total uncertainty of 35% for the values of $r_{32}$, $r_{21}$.

The variation of $r_{32}$, $r_{21}$ across the channel maps from the lower velocities towards the higher ones is much larger than the expected thermal rms variation. In the case of the $r_{32}$ ratio there is an increase by a factor of $\geq 2$. This reveals a significant change in the physical conditions of the gas across the circumnuclear region of NGC 1068. The range of the $r_{32}$ values quoted in the channel map is very similar to the range found in a sample of starburst nuclei by Devereux et al. (1994) where a range of $r_{32} = 0.5 - 1.2$ is measured over scales of $\sim 1$ kpc. Values as high as $r_{32} \sim 1$ are found in cores of star forming Giant Molecular Clouds (GMC’s) like W3 and W51 and are indicative of warm and dense gas, while lower values like $r_{32} \sim 0.3 - 0.4$ characterize the bulk of the gas in GMC’s, which is usually colder (Sanders et al. 1993).
trends, albeit less pronounced, are discernible for the \( r_{21} \) ratio. This ratio is less sensitive than the \( r_{32} \) to the excitation conditions; nevertheless its values vary in a similar fashion (Figure 4.9).

It is also interesting to note that even with the significantly reduced angular resolution afforded by our single dish measurements we find some of the highest \( r_{32} \) ratios towards regions where the GMC's have the highest peak brightness temperatures measured in the high resolution interferometric maps of \(^{12}\text{CO} \ J=1-0\) (Planesas, Scoville & Myers 1991; Helfer & Blitz 1995). This suggests that brightness temperature differences of \(^{12}\text{CO} \ J=1-0\), the most common molecular gas mass tracer, may not entirely reflect differences in \( \text{H}_2 \) mass surface density but may be significantly dependent on the excitation conditions of the gas. In the next chapter we will present a detailed model of the molecular gas emission in NGC 1068 and further explore this possibility.
Figure 4.8: Contour map: The $T_{mb}(3 - 2)$ of $^{12}$CO at a resolution of 16". The rms noise is $\sigma_{32} = 0.065$ K and the contour levels are (3, 5, 7, 9, 11, 13, 15, 17, 19) x $\sigma_{32}$. Gray-scale map: The $T_{mb}(1 - 0)$ of $^{12}$CO at the same spatial and frequency resolution. The rms noise is $\sigma_{10} = 0.080$ K with an intensity scale of $T_{mb}(1 - 0) = 0.25 - 2.5$ K. The velocity of each channel is shown at the upper-right and the $r_{32} = (3 - 2)/(1 - 0)$ within a radius $R \leq 30"$ at the bottom-left of each frame. The HPBW is shown at the bottom right of the first frame.
Figure 4.9: *Contour map*: The $T_{mb}(2 - 1)$ of $^{12}$CO at a resolution of $24''$. The rms noise is $\sigma_{21} = 0.050$ K and the contour levels are $(3, 5, 7, 9, 11, 13, 15, 17, 19) \times \sigma_{21}$.

*Gray-scale map*: The $T_{mb}(1 - 0)$ of $^{12}$CO at the same spatial and frequency resolution. The rms noise is $\sigma_{10} = 0.070$ K with an intensity scale of $T_{mb}(1 - 0) = 0.20 - 1.8$ K. The velocity of each channel is shown at the upper-right and the $r_{21} = (2 - 1)/(1 - 0)$ within a radius $R \leq 30''$ at the bottom-left of each frame. The HPBW is shown at the bottom right of the first frame.
4.4.2 The $^{13}$CO J=3–2, 2–1 maps

For the $^{13}$CO J=2–1 grid map (Figure 4.5) we followed the same interpolation procedure used for $^{12}$CO J=2–1, which results in a map with an effective resolution of $\theta_i = 24''$ which we then analyzed in AIPS. The $^{13}$CO J=2–1 grid map is somewhat smaller than the corresponding $^{12}$CO J=2–1 map (Figure 4.4), even though it fully samples the detected $^{12}$CO emission. In order to avoid some edge truncation effects caused by the AIPS re-gridding task HGEOM, which makes the effective size of the $^{13}$CO J=2–1 map even smaller, we “filled-in” all the unsampled grid points of $^{13}$CO J=2–1 that are observed in $^{12}$CO J=2–1 with a noise spectrum. We verified that this has no effect in the intensity distribution of the interpolated and re-gridded $^{13}$CO J=2–1 map by estimating the area-averaged T$_{mb}$ and comparing it to the one obtained from the original grid map. The two values obtained are in good agreement.

The maps of the velocity-averaged main beam brightness $\langle T_{mb}\rangle_{\Delta v}$ of $^{12}$CO, $^{13}$CO J=2–1 where $\Delta v = 950 - 1300$ km s$^{-1}$ (FWZI) are shown in Figure 4.10.

In order to obtain an interpolated map of the weak $^{13}$CO J=3–2 line with a higher S/N ratio we used a slightly larger interpolating gaussian $\theta_G = 10''$ than the one used for the $^{12}$CO J=3–2 channel maps (Section 4.4.1). This results in an effective resolution of $\theta_i = 17''$. In this case, we did not “fill-in” any “edge” grid-spectra of the $^{13}$CO map since its size is significantly smaller than that of $^{12}$CO and we did not want to introduce any biases in the interpolated line intensities near the map edges. The maps of $\langle T_{mb}\rangle_{\Delta v}$ of $^{12}$CO, $^{13}$CO J=3–2 are shown in Figure 4.11.

It is apparent from both sets of maps that the $^{13}$CO shows a different morphology than the $^{12}$CO emission. More specifically, there is a significant increase of the intensity of $^{13}$CO relative to $^{12}$CO towards the location of the massive and bright molecular gas complex(es) in the southern part of the circumnuclear region of NGC 1068. These molecular gas concentrations show up in high resolution maps (Planesas, Scoville & Myers 1991; Helfer & Blitz 1995) as high brightness regions with large inferred H$_2$ surface densities. Towards the same locations, we measure the highest $r_{21}$, $r_{32}$ line ratios in this galaxy, a clear indication of changing gas excitation conditions.
Figure 4.10: The $\langle T_{mb} \rangle_{\Delta v}$ maps of $^{12}$CO, $^{13}$CO J=2–1 with $\Delta v = 950 - 1300$ km s$^{-1}$, at a resolution of $\theta_1 = 24''$.

*Top:* $^{12}$CO, the rms noise is $\sigma_{12} \approx 0.025$ K. The contours are (3, 5, 7, 9, 11, 13, 15, 17, 19, 21) $\times$ $\sigma_{12}$, while the greyscale range is 0.075–0.535 K.

*Bottom:* $^{13}$CO J=2–1, the rms noise is $\sigma_{13} \approx 0.003$ K. The contours are (3, 5, 7, 9, 11, 13, 15) $\times$ $\sigma_{13}$, while the greyscale range is 0.009–0.048 K.
Figure 4.11: The $\langle T_{mb}\rangle_{\Delta v}$ maps of $^{12}\text{CO}$, $^{13}\text{CO}$ J=3–2 with $\Delta v = 950 - 1300$ km s$^{-1}$, at a resolution of $\theta_i = 17''$.

*Top:* $^{12}\text{CO}$, the rms noise is $\sigma_{12} \approx 0.020$ K. The contours are (3, 5, 7, 9, 11, 13, 15, 17, 19, 21) $\times \sigma_{12}$, while the greyscale range is 0.060–0.456 K.

*Bottom:* $^{13}\text{CO}$ J=3–2, the rms noise is $\sigma_{13} \approx 0.002$ K. The contours are (3, 5, 7, 9, 11, 13)$\times\sigma_{13}$, while the greyscale range is 0.006–0.026 K.
The offsets from the map center (see Table 4.1) are the following
Position A: \((\Delta a, \Delta \delta) = (8'', 0'')\), Position B: \((\Delta a, \Delta \delta) = (-8'', -3'')\)

4.4.3 \textbf{C}^{18}\text{O}, \text{^{13}CO} \text{ J}=2–1 spectra at two positions

We measured the C^{18}O J=2–1 spectrum in two positions in NGC 1068, with a spatial resolution of \(\theta_{\text{HPBW}} = 22''\). In order to compare them with similar resolution to \(^{13}\text{CO}\) spectra from the same locations we produced these spectra from an interpolated \(^{13}\text{CO}\) J=2–1 map with \(\theta_{\text{C}} = 8''\), which results in an effective resolution of \(\theta_{\text{I}} = 23''\) which is close to the resolution of the C^{18}O data. We then smoothed the spectra to a common frequency resolution of 25 MHz (34 km s\(^{-1}\)) and we show them in Figure 4.12 above.

The ratio \(R_{21}^{(18)} = \text{C}^{18}\text{O}/^{13}\text{CO} \text{ J}=2–1\) using corresponding measurements of \(\langle T_{\text{mb}} \rangle_{\Delta v}\) (\(\Delta v = 950 – 1300 \text{ km s}^{-1}\)) obtained at these two positions is \(R_{21}^{(18)} (A) = 0.26 \pm 0.07\) and \(R_{21}^{(18)} (B) = 0.20 \pm 0.06\). These values, while somewhat lower, are comparable to the average ratio \(R_{10}^{(18)} = 0.3 \pm 0.1\) found from our high resolution OVRO maps (Section 4.2). This confirms our earlier conclusion that the C^{18}O/^{13}CO intensity ratio is significantly higher than the average value observed in the Milky Way.
Chapter 5

NGC 1068: Physical conditions of the molecular gas

5.1 Average conditions of the molecular gas

The main purpose of our study of the archetypal Sy2/starburst galaxy NGC 1068 is to study in detail the physical properties of the gas in its starbursting circumnuclear region. This requires fully sampled maps so that line ratios can be estimated reliably without the frequently employed ad hoc assumptions about the source size and brightness distribution. At the same time the observation of the highest CO transition that can be (almost) routinely accessed from the ground, namely J=3–2 for both the $^{12}$CO, $^{13}$CO isotopes, enables us to examine a wider range of molecular gas excitation conditions. This transition becomes a particularly sensitive gas excitation probe when compared to the lowest transition J=1–0. In the present study we are able to estimate the intensity ratio $r_{32}$ (for $^{12}$CO) at the highest angular resolution currently possible ($\sim 16''$) thus allowing this sensitive gas excitation probe to provide us with information about the physical conditions of the molecular gas towards particular locations within the starburst nuclear region of NGC 1068.

A simple inspection of the channel maps in Figures 4.8, 4.9 and the varying $r_{32}$, $r_{21}$ line ratios, and a comparison of the maps of the velocity-averaged brightness temperatures for $^{12}$CO and $^{13}$CO J=2–1, 3–2 (Figures 4.10, 4.11), readily shows that
the physical conditions of the molecular gas vary within the inner 60″ of NGC 1068. From this point of view it may no longer seem useful to talk about the average physical conditions of the molecular gas in NGC 1068 as reflected by the area-averaged spectral lines and their ratios.

However this is still interesting since it allows us a comparison of the results of the present study with already existing multi-line studies of Active Galaxies, where usually the telescope beam samples the entire emitting region in one or very few pointings and thus “averages-in” molecular gas in a variety of physical states. Moreover, a comparison of the “average” properties of the molecular gas over the entire CO-emitting region to the ones deduced over smaller scales allows one to examine the degree to which global averages are affected by the observed small scale variations of the gas excitation. This is important since estimates of total molecular gas mass in galaxies are based in the so-called standard Galactic conversion factor that converts the area-averaged quantity \( L_{\text{CO}} = \int_{\text{area}} \int_{\Delta \nu} T_b \ dv \ d\Omega \) for \(^{12}\text{CO} \ J=1-0\) to global molecular gas mass by assuming a value for \( X_c = M(\text{H}_2)/L_{\text{CO}} \) found for molecular clouds in the Milky Way.

We find the global spectra of NGC 1068 by estimating the quantity

\[
T_{\text{mb}}^{(G)}(v) = \frac{1}{\Omega_c} \int_{\Omega_c} T_{\text{mb}}(v, \Omega) \ d\Omega
\]

where \( \Omega_c \) is the beam solid angle corresponding to a circle centered on the map center with a radius of \( R = 30″ \), which contains the entire CO-emitting region.

These spectra are shown in Figure 5.1. A striking property of these spectra is that the \( J=3-2, 2-1 \) transitions reveal a markedly different pattern than the \( J=1-0 \) for both isotopes \(^{12}\text{CO} \) and \(^{13}\text{CO} \). The ratio of \(^{12}\text{CO} / ^{13}\text{CO} \) barely changes across the line profiles of the \( J=3-2, 2-1 \) transitions while it changes by a factor of \( \sim 2 \) in the case of \( J=1-0 \) from the low to the high velocities. Moreover the area-averaged main beam brightness temperature of both \(^{12}\text{CO} \) and \(^{13}\text{CO} \) changes significantly more across the profile of the \( J=1-0 \) transition than the profiles of the higher \( J=3-2, 2-1 \) transitions.
Figure 5.1: Global spectra of $^{12}$CO, $^{13}$CO for $J=3-2$, $2-1$, $1-0$

\[ T_{mb}(v) = T_{mb}^{(G)}(v) \] (see Equation 5.1)
5.1.1 The “missing” $^{13}$CO $J$=1–0 flux

The $J$=1–0 line exhibits a classic double-horn profile in both $^{12}$CO and $^{13}$CO isotopes which appears more prominently in the latter one. However the $^{12}$CO BIMA/NRAO data by Helfer & Blitz (1995) demonstrates that the addition of the single dish data leaves the two outer kinematic components at $V_{\text{LSR}} \sim 1000$ km s$^{-1}$ and $V_{\text{LSR}} \sim 1250$ km s$^{-1}$ unchanged while increasing the strength of the component at the systemic velocity by a factor of $\sim 2$.

This is expected since the most extended CO emitting regions in a galaxy usually appear at its systemic velocity, while the outlying velocities are usually associated with more compact emission. For this reason our OVRO $^{13}$CO $J$=1–0 global spectrum is reliable for estimating the relative strength of the $^{12}$CO, $^{13}$CO $J$=1–0 transitions only for the two outer kinematic components which correspond to the easternmost and westernmost parts of the $^{13}$CO $J$=1–0 emission seen in Figure 4.1.

It is important to emphasize here that the $^{12}$CO $J$=1–0 global spectrum contains all the CO flux and shows a different, double-horn, line profile than the $J$=2–1, 3–2 transitions. Thus, the addition of the single dish flux of $^{13}$CO to the OVRO data would not change the basic double-horn profile of the $^{13}$CO $J$=1–0 spectrum either. Examination of the $^{13}$CO $J$=1–0 global spectrum estimated from the Helfer & Blitz map (which contains all the $^{13}$CO flux) reveals the same features as our OVRO spectrum. Most importantly it shows a similar variation of a factor of $\sim 2$ for the $R_{10}$ ratio for the two outer kinematic components. Similar variations of $R_{10}$ are also found when comparing $^{12}$CO, $^{13}$CO $J$=1–0 interferometric maps obtained with OVRO (Planesas et al. 1991; Papadopoulos et al. 1996).

Thus the variation of $R_{10}=^{12}$CO/$^{13}$CO $J$=1–0 line ratio and the $T_{\text{mb}}^{(G)}(v)$ intensity of $^{12}$CO $J$=1–0 seen across the line profile is real. Finally the reason for not using the BIMA $^{13}$CO $J$=1–0 spectrum itself, even though it has been augmented by single-dish data, is because it is significantly noisier than our OVRO spectrum.
5.1 NGC 1068: The global line ratios

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<td>(^{12}\text{CO}(3-2)) / (^{13}\text{CO}(1-0))(^{\text{a}})(^\text{b})</td>
<td>0.52 ± 0.17</td>
<td>(^{12}\text{CO}(2-1)) / (^{13}\text{CO}(1-0))(^{\text{c}})</td>
<td>0.68 ± 0.23</td>
<td>(^{12}\text{CO}(3-2)) / (^{13}\text{CO}(3-2))(^{\text{a}})(^\text{b})</td>
<td>14 ± 3</td>
<td>(^{12}\text{CO}(2-1)) / (^{13}\text{CO}(2-1))(^{\text{a}})</td>
<td>10 ± 2</td>
<td>(^{12}\text{CO}(1-0)) / (^{13}\text{CO}(1-0))(^{\text{c}})</td>
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\(^{\text{a}}\) OVRO measurement (page 54), Young & Sanders (1986).
\(^{\text{b}}\) OVRO measurement (page 58).
\(^{\text{c}}\) The average of the two values measured with the JCMT (page 78).

5.2 The global line ratios, LVG modeling

We used the global spectra presented in the previous section in order to estimate the average line ratios over the entire emitting region of NGC 1068. The values of these ratios and their associated uncertainties are presented in Table 5.1 above. The major uncertainty characterizing the values of the \(r_{32}\) and \(r_{21}\) ratios is the \(\sim 30\%\) flux calibration uncertainty of the BIMA \(^{12}\text{CO}\) J=1–0 map.

We searched an extensive grid of LVG models with a parameter range of \(T_{\text{kin}} = 6 - 150\) K (\(\Delta T_{\text{kin}} = 2\) K), \(n(\text{H}_2) = (0.1 - 10^4) \times 10^3\) cm\(^{-3}\) (\(\Delta \log n(\text{H}_2) = 0.5\)) and, \(\Lambda = (0.1 - 10^2) \times 10^{-6}\) km s\(^{-1}\) pc\(^{-1}\) (\(\Delta \log \Lambda = 0.5\)). We assumed an abundance of \([^{12}\text{CO} / ^{13}\text{CO}] = 40\) since studies of the Milky Way (Langer & Penzias 1993) and nuclear regions of starburst galaxies (Henkel at al. 1993; Henkel & Mauersberger 1993) show this value to be a suitable average of the abundances observed towards galactic nuclear regions. The abundance of \([^{13}\text{O}^{18}\) / \(^{13}\text{CO}\] = 0.15 is derived from \([^{12}\text{CO} / ^{13}\text{CO}] = 40\) and \([^{12}\text{CO} / ^{13}\text{O}^{18}] = 250\), which is the highest such value derived for molecular clouds in the Milky Way (Wannier 1980), and was measured towards its center. The results of this LVG fit are summarized in Table 5.2

We examine the entire grid of the LVG models for the values of \(r_{21}, r_{32}\) that correspond to 0\%, -30\% and +30\% offset in the BIMA \(^{12}\text{CO}\) J=1–0 intensity. The best fit is found for the highest \(r_{21}, r_{32}\) ratios corresponding to the 30\% reduction in the flux density of the \(^{12}\text{CO}\) J=1–0 map.
The possibility that the BIMA data may underestimate the \(^{12}\text{CO} J=1-0\) intensity by as much as \(\sim 30\%\) seem to be supported by single dish measurements of the velocity-integrated intensity of this line reported by Maiolino et al. (1997) and Kaneko et al. (1989). The first used the NRAO 12m to obtain a velocity-integrated main beam brightness for the inner 55\" \times 55\" of NGC 1068 which they measured to be \(I_1 = (90 \pm 13) \text{K km s}^{-1}\), while the latter used the NRO 45m telescope to map the inner 60\" \times 60\" and found \(I_2 = (83 \pm 17) \text{K km s}^{-1}\). We deduced these values from their data after converting the \(T^*_R\) (NRAO 12m) and \(T^*_A\) (NRO 45m) temperature scales to \(T_{mb}\). The integrated flux we find over the same region using the BIMA map is \(I_{\text{BIMA}} = (131 \pm 40) \text{K km s}^{-1}\). Clearly only a large offset of \(\approx -30\%\) can bring the BIMA value in agreement with the other two values. Moreover, adopting such an offset yields \(r_{21} = 0.97\), which in much better agreement with the value \(r_{21} = 1.1\) reported by Braine & Combes (1992) (see Table 3.1) for the same region of the galaxy than the measured value \(r_{21} = 0.68\).

It is interesting to note that Thronson et al. (1987) using mm/sub-mm continuum measurements deduce a dust temperature of \(T_d = 20 \text{K}\) for the inner 55\" of this galaxy, which is very similar to the gas temperatures we find from the LVG fit and identical to the one corresponding to the best fit (Table 5.2). This is expected for well mixed gas and dust and it also suggests that the \(^{12}\text{CO}, \:^{13}\text{CO}\) lines trace the same “average” conditions as the mm/sub-mm emission. This is important since \(^{12}\text{CO}\) in particular can have substantial optical depth.

From Table 5.2, we can see that the single-phase LVG model fails to provide a good fit in the case of low \(r_{32}, r_{21}\) ratios. For values of \(r_{32} \sim 0.4 - 0.5\), it gives ratios \(r_{21} > 0.7\), significantly larger than the ones used for the fit. The largest discrepancy found is in the value of \(R_{32}\) where the one inferred by the best-fit LVG model is significantly larger than the one used for the fit, thus demonstrating the sensitivity of the \(J=3-2\) transition to the assumed gas excitation conditions. We will discuss the physical reasons behind these discrepancies in more detail in the next section where we introduce a two-phase model for the molecular gas in NGC 1068.

There are two basic characteristics of the inferred global gas excitation conditions
that readily stand out. One is the fact that no successful fit can be found that includes the $^{18}\text{O}/^{13}\text{CO}$ line ratios. This is because, for an assumed abundance of $[^{18}\text{O}/^{13}\text{CO}] = 0.15$ (the highest value inferred for the Milky Way), the observed value $R_{10}^{(18)} \sim 0.30$ implies substantial optical depth ($\tau \geq 2$) for $^{13}\text{CO}$, which would then result in $R_{10} \sim R_{21} \sim R_{32} \sim 1$, contrary to what is observed. This confirms earlier conclusions in Section 4.2.2 that $^{18}\text{O}$ seems to trace a different gas component than either $^{12}\text{CO}$ or $^{13}\text{CO}$.

The other interesting aspect of the LVG solutions is that the deduced optical depth of the $^{12}\text{CO}$ $J=1-0$ transition is moderate $\tau_{10} \sim 1 - 2$. This was suggested by Aalto et al. (1995) as being one of the characteristics of a second, more diffuse and warm gas phase that accompanies a dense and spatially more concentrated one in the nuclear regions of starbursts (see also Wall et al. 1993 for earlier work on spirals). This would naturally explain why both the average brightness of the $^{12}\text{CO}$ $J=1-0$ transition as well as the $R_{10}$ line ratio seem to be more sensitive functions of velocity (and therefore of location within the galaxy) than the $J=2-1$, $3-2$ transitions and the $R_{21}$, $R_{32}$ ratios. A simple LTE argument can illustrate the point. The optical depth $\tau_{J+1,J}$ of the $^{12}\text{CO}$ $J+1\rightarrow J$ transition can be expressed as a function of $T_{\text{kin}}$ and the optical depth $\tau_{10}$ of the $J=1-0$ transition as follows:

$$\tau_{J+1,J} = (J + 1) \frac{1 - e^{-\Delta E_{J+1,J}/kT_{\text{kin}}}}{1 - e^{-\Delta E_{10}/kT_{\text{kin}}}} \tau_{10}$$

(5.2)

where $E_J$ is the energy of the $J$ rotational level and $\Delta E_{J+1,J} = E_{J+1} - E_J$ with $E_0/k = 0$ K, $E_1/k = 5.53$ K, $E_2/k = 16.60$ K, $E_3/k = 33.20$ K.

For a temperature of $T_{\text{kin}} \geq 20$ K which is the minimum kinetic temperature deduced from the LVG modeling and the independent mm/sub-mm continuum measurements by Thronson et al. (1987) we get $2.7\tau_{10} \leq \tau_{21} \leq 4\tau_{10}$ and $3\tau_{10} \leq \tau_{32} \leq 9\tau_{10}$.

A moderate optical depth $\tau_{10} \sim 1 - 2$ for the $^{12}\text{CO}$ $J=1-0$ transition will give $\tau_{J+1,J} \sim 3 - 6$ ($J=1,2$). This range of $\tau_{10}$ values is more or less the one that allows the brightness of the $J=1-0$ transition to be significantly more sensitive than the $J=2-1$, $3-2$ to variations of gas column density and excitation conditions.
Table 5.2  LVG models: The global line ratios

<table>
<thead>
<tr>
<th>Physical conditions(^a)</th>
<th>Line ratios(^b)</th>
<th>Excitation characteristics(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{kin}} = 22 ) K (&lt;br&gt; n(H_2) = 3 \times 10^3 \text{ cm}^{-3} ) (&lt;br&gt; \Lambda = 3 \times 10^{-6} \text{ (km s}^{-1} \text{ pc}^{-1})^{-1} ) (&lt;br&gt; ^{12}\text{CO}(1-0) \text{ offset: 0%} ) ( \chi_{\text{min}} = 2.31 \ (2.74, 2.63))</td>
<td>( r_{32} = 0.52 \pm 0.08 \ (0.56) ) (&lt;br&gt;r_{21} = 0.68 \pm 0.12 \ (0.89) )</td>
<td>( ^{12}\text{CO}: \ T_R(1-0) = 13 ) K (&lt;br&gt;(E_{10}, \tau_{10}) = (0.87, 1.9) ) (&lt;br&gt;(E_{21}, \tau_{21}) = (0.78, 5.4) ) (&lt;br&gt;(E_{32}, \tau_{32}) = (0.65, 6.1) )</td>
</tr>
<tr>
<td>( T_{\text{kin}} = 20 ) K (&lt;br&gt;n(H_2) = 1 \times 10^4 \text{ cm}^{-3} ) (&lt;br&gt;\Lambda = 1 \times 10^{-5} \text{ (km s}^{-1} \text{ pc}^{-1})^{-1} ) (&lt;br&gt;^{12}\text{CO}(1-0) \text{ offset: -30%} ) ( \chi_{\text{min}} = 0.60 \ (1.75, 1.54))</td>
<td>( r_{32} = 0.74 \pm 0.11 \ (0.75) ) (&lt;br&gt;r_{21} = 0.97 \pm 0.17 \ (0.99) )</td>
<td>( ^{13}\text{CO}: \ T_R(1-0) = 13 ) K (&lt;br&gt;(E_{10}, \tau_{10}) = (0.97, 1.7) ) (&lt;br&gt;(E_{21}, \tau_{21}) = (0.92, 4.8) ) (&lt;br&gt;(E_{32}, \tau_{32}) = (0.84, 5.4) )</td>
</tr>
<tr>
<td>( T_{\text{kin}} = 28 ) K (&lt;br&gt;n(H_2) = 1 \times 10^3 \text{ cm}^{-3} ) (&lt;br&gt;\Lambda = 1 \times 10^{-5} \text{ (km s}^{-1} \text{ pc}^{-1})^{-1} ) (&lt;br&gt;^{12}\text{CO}(1-0) \text{ offset: +30%} ) ( \chi_{\text{min}} = 3.75 \ (4.13, 3.94))</td>
<td>( r_{32} = 0.40 \pm 0.06 \ (0.40) ) (&lt;br&gt;r_{21} = 0.52 \pm 0.09 \ (0.77) )</td>
<td>( ^{12}\text{CO}: \ T_R(1-0) = 13 ) K (&lt;br&gt;(E_{10}, \tau_{10}) = (0.63, 2.2) ) (&lt;br&gt;(E_{21}, \tau_{21}) = (0.53, 6.5) ) (&lt;br&gt;(E_{32}, \tau_{32}) = (0.41, 6.7) )</td>
</tr>
</tbody>
</table>

\(^a\) The physical conditions of the best fit of the line ratios of the transitions of \(^{12}\text{CO}, \ ^{13}\text{CO}\).<br>\( \Lambda = \frac{X}{(dV/dR)} \), \( X = \frac{[^{12}\text{CO}]}{H_2} \) and \( \chi^2 = \sum_i \frac{1}{\sigma_i^2} \left( R_{\text{obs}}^{(i)} - R_{\text{LVG}}^{(i)} \right)^2 \), where \( R^{(i)}, \sigma_i \) are the observed line ratios and the 1 \( \sigma \) error and \( R_{\text{LVG}}^{(i)} \) are the ones deduced from the LVG fit.<br>

\(^b\) The line ratios with their rms errors with the LVG-deduced ones in the parentheses.<br>

\(^c\) \( T_R(1-0) \) is the LVG-deduced brightness of \(^{12}\text{CO} \ J=1-0 \) and \( E_{J+1,J} = \frac{T_{\text{ex}}(J+1,J)}{T_{\text{kin}}} \) measures the excitation state of each \( J+1 \rightarrow J \) transition and \( \tau_{J+1,J} \) its optical depth.<br>

\(^d\) The \( \chi_{\text{min}} \) of the fit that includes a) both \( R_{10}^{(18)} \) and \( R_{21}^{(18)} \), b) only \( R_{10}^{(18)} \).
A range of higher values $\tau_{10} > 2$ would render all three transitions optically thick and the resulting radiative trapping would lead to their thermalization even at moderate/low ($n(H_2) \leq 10^3$ cm$^{-3}$) gas densities. Such transitions would then be equally “insensitive” to the conditions of the molecular gas other than the kinetic temperature. For an average gas temperature of $T_{\text{kin}} \geq 20$ K and optically thick and thermalized $^{12}$CO the sensitivity of the ratios $r_{21}$ and $r_{32}$ to $T_{\text{kin}}$ is drastically reduced. In such a case the observed variations of these ratios that are beautifully demonstrated in Figures 4.8, 4.9 cannot be due to variations of $T_{\text{kin}}$ of gas that is optically thick and thermalized in $^{12}$CO.

On the other hand significantly lower values $\tau_{10} < 0.2$ will result in all three transitions being in the optically thin/moderate optical depth regime and therefore all of them being sensitive to the excitation conditions of the gas and their variations within the galaxy. In this case one would expect that the global line profiles of all three transitions $J=1 \rightarrow 0$, $2 \rightarrow 1$, $3 \rightarrow 2$ and the line ratios $R_{10}$, $R_{21}$, $R_{32}$ to exhibit strong variations as a function of velocity.

Another important consequence of the relatively high average gas densities and the moderate $^{12}$CO $J=1 \rightarrow 0$ optical depths is the slight super-thermal excitation of $^{13}$CO $J=1 \rightarrow 0$, i.e., $E_{10} > 1$ for the two best LVG solutions in Table 5.2. We discussed this feature of the $J=1 \rightarrow 0$ transition in Chapter 3 (pg 45) which occurs for small optical depths ($\tau \leq 0.1$) and therefore it is expected for $^{13}$CO and $^{18}$O. In this regime the ratio of the optical depths $\tau_{J+1} / \tau_{10}$ ($J=1,2$) for $^{13}$CO and $^{18}$O can significantly exceed their LTE values given by Equation 5.2 (see Table 5.2). This will contribute further towards making the $R_{10}$ line ratio significantly more sensitive to local conditions of the gas than the $R_{21}$ and $R_{32}$ ratios.

It was this feature of the $J=1 \rightarrow 0$ transition that allows line ratios like $r_{21} \sim 0.8 - 1.0$ and $R_{10} > R_{21}$ to be fitted by a single gas phase over a wide range of $n(H_2)$ and $\Lambda$ without having to necessarily resort to a two-component model. Here we emphasize that this feature of the CO excitation is quite insensitive to the structure of the velocity field, and hence very likely to occur and even characterize the $^{13}$CO $J=1 \rightarrow 0$ (and $^{18}$O) emission over an entire gas phase whose physical properties satisfy the
conditions described on page 45. As we will see in the following section, this seems to be the case for one of the two distinct gas phases that dominate the observed CO emission in the central region of NGC 1068.

As we said at the beginning of this section the LVG fit of the global ratios is useful only as a rough guide on the average conditions expected in the inner 3-4 kpc of this galaxy and to demonstrate the inadequacy of such a method in providing anything more than such a rough average. In this case it is the C\textsuperscript{18}O measurements that provide the crucial piece of information that clearly demonstrates that a single gas phase cannot represent the gas in the circumnuclear starbursting region of NGC 1068. However we now have a clearer picture of the range of the physical conditions that are present in order to reproduce the observed line ratios. In the following two sections we describe these conditions in more detail and examine to what extent the usual methods employed to deduce molecular gas mass are still reliable in environments like the one encountered in the starbursting circumnuclear region of NGC 1068.

5.3 The heterogeneous gas in starburst nuclei and two types of molecular clouds

The notion of a two-component or generally multi-component molecular gas phase may seem rather trivial given the fact that numerous studies in the Milky Way as well as in other galaxies using a variety of molecules and their transitions reveal molecular gas with a large range of temperatures \( T_{\text{kin}} \sim 10 - 100 \) K and densities \( n(\text{H}_2) \sim 10^2 - 10^8 \) cm\(^{-3}\). This notion is indeed not particularly useful if one does not include the spatial scale involved. For example examination of the physical conditions of the molecular gas on scales of \( L \leq 1-50 \) pc is bound to yield a very different picture depending on whether one looks at Orion-type molecular clouds that harbor ongoing star formation or more quiescent clouds. However averaging over much larger scales \( L \geq 0.5 \) kpc starts “smoothing” out the local density and temperature irregularities to a degree that when one deduces the temperature \( T_{\text{kin}} \) and density \( n(\text{H}_2) \) implied
by molecular line spectroscopy it yields a significantly narrower range of \((n(H_2), T_{\text{kin}})\) fitting the observed line ratios.

*It is when such “averaging” fails to converge towards a single narrow set of physical conditions that the notion of more than one molecular gas component becomes meaningful and necessary.*

Here we must mention that while examination of the molecular gas properties averaged over scales of \(L \geq 0.5\) kpc may yield a single narrow range of density and temperature, this range is by no means constant across a galaxy. Numerous studies of molecular gas in other galaxies (e.g., Eckart et al. 1991; Braine & Combes 1992; Aalto et al. 1995; this work Section 3.3.1) have demonstrated a broad differentiation of molecular gas properties with warm \((T_{\text{kin}} \geq 20\) K) and dense gas \((n(H_2) \geq 10^4\) cm\(^{-3}\)) lying in the nuclear region \(\sim 0.5 - 1\) kpc while colder \((T_{\text{kin}} \leq 10\) K), less dense \((n(H_2) \leq 10^3\) cm\(^{-3}\)) gas is located further out in the disk. A similar differentiation seems to be in place in the Milky Way (e.g., Bally et al. 1988; Stark et al. 1991; Binney et al. 1991; Spergel & Blitz 1992). The properties of the molecular clouds in galactic disks seem to be easily described by a single set of molecular gas properties or, equivalently, the “averaging” of those properties over scales of \(L \geq 0.5\) kpc converges to a single type of “average” cloud.

This, however, does not seem to be the case for the molecular gas that lies in the nuclear region. Several studies (e.g., Wall & Jaffe 1990; Eckart et al. 1990; Wall et al. 1993; Aalto et al. 1995) indicate that even when averaged over 0.5-1 kpc, the line emission of the various trace molecules does not point towards a single gas phase but at least two. We have already discussed these arguments in section 3.5 of this work where we argued that, while the above picture can be true, some of the arguments used to support it are inadequate. The wealth of molecular line data gathered for the circumnuclear region of NGC 1068 now allows for a more rigorous test of these ideas.

In the case of NGC 1068 the interferometric \(^{13}\text{CO}, \ C^{18}\text{O} \ J=1-0\) maps (pages 61, 62) as well the lower resolution \(^{12}\text{CO}, \ ^{13}\text{CO} \ J=3-2, \ 2-1\) maps show a different morphology for the different isotopes. This is a first indication that the various isotopes “look through” different gas components. However averaging over the entire
CO-emitting area smoothes out to a certain degree the variations of the line brightness temperature and the $R_{J+1/J}$ ratios except for the $J = 1 - 0$ transition as it can be seen from the global line profiles in Figure 5.1. Indeed, a comparison of $^{12}$CO, $^{13}$CO J=1–0 interferometric maps (Helfer & Blitz 1995) as well as $^{13}$CO and $^{18}$O J=1–0 (Section 4.2.1) reveals changes of their relative intensity by large factors ($\sim 2 - 3$). LTE arguments as well as more detailed LVG modeling (see Table 5.2) point towards moderate optical depths ($\tau \sim 1 - 2$) for the $^{12}$CO J=1–0 transition, while the values of the $R_{10}^{(18)} = \frac{^{18}\text{O}}{^{13}\text{CO}}$ J=1–0 ratio points towards $\tau_{10}^{(13)} \geq 1$.

Since there is not a single gas phase that can satisfy both requirements this is the most direct evidence that there are indeed at least two distinct gas phases dominating the observed CO emission. One is characterized by $\tau_{10} \sim 1 - 2$; and the other one by $\tau_{10}^{(13)} \geq 1$. A number of other studies (e.g., Eckart et al. 1990; Wall et al. 1990; Wild et al. 1992; Wall et al. 1993; Aalto et al. 1995) have used the high intensity of $^{18}$O relative to $^{13}$CO as evidence of a separate, more concentrated, gas phase with optically thick $^{13}$CO in the centers of starbursts. A similar picture seems to emerge recently for the molecular gas in the Galactic Center (Dahmen et al. 1998) where, in most regions, $^{12}$CO and $^{18}$O J=1–0 observations point towards a warm and diffuse gas phase with $\tau_{10} \sim 1 - 2$ dominating the $^{12}$CO emission.

The two-component gas phase model for the molecular gas in starburst nuclei is not attractive simply because of its phenomenology, i.e., because it fits a whole range of observed line ratios, but also because a significant variety of physical processes that become prominent especially in such regions seem to drive the ambient molecular gas towards such a condition. More specifically Aalto et al. (1995) argued that in a nuclear starburst environment the high gas surface densities (and NGC 1068 with $\Sigma(\text{H}_2) \sim 10^3 \, M_\odot \, \text{pc}^{-2}$ definitely falls in that category) as well as other related factors are responsible for the creation of a diffuse, not self-gravitating and warm gas phase with $\tau_{10} \sim 1$ that dominates the $^{12}$CO emission. In the same regions there exists a second phase that consists of more dense ($n(\text{H}_2) \geq 10^4 \, \text{cm}^{-3}$) and smaller molecular clouds where $^{13}$CO and possible even $^{18}$O may have significant optical depth (i.e., $\tau \sim 1$) and is responsible for most of the observed $^{13}$CO and $^{18}$O emission. Evidence
for such dense molecular gas has been uncovered in a number of studies where $^{13}$O is found to be optically thick (e.g., White 1997).

The following discussion presents a list of the phenomena that may be responsible for causing and maintaining this differentiation process.

a) An intense UV radiation field, expected in a starburst environment, will warm the cloud surfaces and hence reduce their effective optical depth with respect to their inner part since $\tau_{10}$ is very sensitive to temperature. Indeed, in LTE this dependence is

$$\tau_{10} \propto \frac{1 - e^{-5.5/T_{\text{kin}}}}{T_{\text{kin}}}$$

Hence for a $T_{\text{kin}} = 10$ K and $\tau_{10} = 10$ for the cloud interior and $T_{\text{kin}} = 30$ K for the cloud surface, one obtains $\tau_{10} = 1.3$ for the optical depth of the warm outer part. One may be tempted to dismiss such a phenomenon by claiming that it affects only a small part of the cloud and thus not really capable of producing the two-component gas differentiation. However work by Gierens, Stutzki & Winnewisser (1992) demonstrates that in a dense molecular clump UV irradiation alone can still result in gas mass distributions where most of the gas mass is contained in the diffuse gas phase of the “envelope” rather than in the denser core in the center.

b) Aalto et al. (1995) also points to the fact that the large molecular gas surface densities observed in IR-luminous and ultra-luminous galaxies will result in a gas with higher velocity dispersion and large turbulent line widths. This acts towards reducing the average optical depth of the low-density diffuse gas even further since $\tau \propto 1/\Delta V$.

c) Any plausible density profile for individual clouds has a density that decreases with radius, thus the outer parts are more susceptible to heating by the UV radiation field with the effects described above. Such density profiles are used in a recent work by Doty & Neufeld (1998) to indicate that even in the case of very small clouds of sub-parsec size with an embedded protostar where, unlike the processes described up to now, one might expect the central protostar to affect the cloud from the “inside-
out”, the luminosities of the CO J=1–0, 2–1, 3–2 transitions are still regulated by the interstellar radiation field rather than the protostar.

d) Tidal forces that start becoming important towards the galactic centers will tend to “strip” the outer, less dense parts of a giant molecular cloud while leaving the more compact denser regions intact. Then the resulting stripped-out molecular gas gets diffused even further by differential rotation.

e) Cloud-cloud collisions will be on average more frequent in the circumnuclear regions of high H$_2$ surface density rather than the disk, as the molecular clouds are “funneled-in” along a bar to fuel the ongoing star formation there. In such collisions, 1) the larger cross section presented by the outer, less dense layers of the molecular cloud and, 2) the fact that, for a self-gravitating cloud, these layers are more weakly held together than the inner ones makes them more susceptible to the disruption that occurs during such events. The prevalent differential rotation velocity field can then diffuse the disrupted gas even further rather than let it settle again in self-gravitating clouds as it may happen for clouds further out in the disk where a flat rotation curve usually takes over.

All the aforementioned physical processes become particularly prominent in starburst nuclei and act to differentiate the molecular gas into two gas phases. One phase is extended, warm with low density and it originates from the heated and disrupted outer envelopes of molecular clouds. The other one consists of the more “protected” interiors of such clouds where the gas is denser.

5.4 NGC 1068: The two gas phases

Our data set for this archetypal Sy2/starburst galaxy is unique in the sense that this is the first multi-line study where the entire extent of the CO emitting region of an active galaxy is fully mapped in the first 3 rotational transitions of CO isotopes that are routinely accessible from the ground. This allows us to estimate resolution-matched line ratios over the whole area and examine the various CO-emitting regions in more detail. In practice, besides the R$_{10}$ and R$_{10}^{(18)}$ that can be estimated from
interferometer maps (section 4.2), only the ratio $r_{32}$ is estimated at a resolution high enough ($\sim 16''$) to make it a useful probe of varying gas excitation conditions within the star-forming region of NGC 1068. Hence, while a telescope with a beam size of $\sim 60''$ would record the area-averaged line profiles seen in Figure 5.1, the maps in Figures 4.1, 4.8, 4.9, allow the identification of the various kinematic components and the corresponding line ratios seen in those profiles with spatially resolved features in the maps.

The analysis of properties of the molecular gas in NGC 1068 is significant beyond the scope of simply deducing the physical conditions of the gas for this particular galaxy. The reason for this is that a diffuse gas phase that may be dominating the $^{12}\text{CO}$ emission in starburst nuclei may not be self-gravitating and therefore the associated linewidth will not reflect gas mass. In this case the standard way of deducing gas mass, by using the luminosity of the $^{12}\text{CO}$ J=1–0 line and the standard galactic conversion factor (see Bryant & Scoville 1996 for recent work) will overestimate the amount of gas present. In NGC 1068 we have the opportunity of using a variety of line data to constrain the conditions of the gas and estimate the amount of mass contained in such a diffuse non-virialized component as well as in a denser, more optically thick and spatially concentrated one. This in turn gives us valuable information about deducing gas mass in extreme environments.

Hints that a diffuse, non-virialized gas phase may comprise a significant fraction of the gas in starburst nuclei can be found without resorting to a detailed analysis that uses a two-phase gas model. As we will see in the section that follows the values of $\Lambda$ and $n(\text{H}_2)$ deduced from a single-phase LVG model, can be used to examine the possibility of a non-virialized gas phase.

### 5.4.1 Gas kinematics and the range of dV/dr

For a range of temperatures of $T_{\text{kin}} \sim 10 - 50$ K the expected thermal line width is $\Delta v_{\text{th}} = 0.1 - 0.2$ km s$^{-1}$. For the LVG approximation to be valid the line width of the average cloud has to be significantly larger than $\Delta v_{\text{th}}$, which is what we usually observe. Let’s assume that the minimum velocity width satisfying the LVG criterion
is of the order of $\Delta v = 10 \times \Delta v_{\text{th}} = 1 - 2$ km s$^{-1}$. On the other hand since
the observed line width in extragalactic observations is made from several clouds it restricts
the maximum linewidth for a single "average" cloud to a fraction of the total observed width. Assuming a typical extragalactic line width to be $\Delta v_G = 500$ km s$^{-1}$ and made of the linewidths of at least 10 clouds yields an approximate maximum line width of $\Delta v_{\text{max}} = 0.1 \times \Delta v_G = 50$ km s$^{-1}$. This is a rather generous upper limit since the dispersion seen in individual Galactic GMCs is of the order of $\Delta v = 3 - 8$ km s$^{-1}$ (Scoville & Good 1989). For a typical cloud size of $L = 1 - 10$ pc and an assumed abundance of $[^{12}\text{CO}]/\text{H}_2 = 10^{-4}$ we get a range for $\Lambda$ of the order of $\Lambda = \text{few} \times (10^{-6} - 10^{-3})$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$.

If the "average" cloud is virialized, then the expected range for $dV/dr$ will be narrower. For a spherical cloud of radius $R$ the virial theorem gives:

$$
\left(\frac{dV}{dr}\right)_{\text{vir}} = \frac{\delta V_{\text{vir}}}{2R} = \left(\frac{\alpha \pi G \mu}{3}\right)^{1/2} \langle n \rangle^{1/2},
$$

(5.4)

where $\mu$ is the mean mass per particle and $\langle n \rangle$ is the mean number density of the cloud. The factor $\alpha \sim 0.5 - 2.5$ depends primarily on the assumed density profile (see Bryant & Scoville 1996). Expressing the last result in astrophysical units gives

$$
\left(\frac{dV}{dr}\right)_{\text{vir}} = 0.65\alpha^{1/2} \left(\frac{\langle n \rangle}{10^4 \text{cm}^{-3}}\right)^{1/2} \text{km s}^{-1} \text{ pc}^{-1}.\tag{5.5}
$$

In the case of NGC 1068, the best LVG solution of the global ratios gave (Table 5.2) $\langle n \rangle = 1 \times 10^4$ cm$^{-3}$, so for the largest reasonable value of $\alpha = 2.5$ we estimate $(dV/dr) \sim 3$ km s$^{-1}$ pc$^{-1}$. The LVG modeling also gave $\Lambda = 10^{-6}$ km s$^{-1}$ pc$^{-1}$, which for $[^{12}\text{CO}]/\text{H}_2 = 10^{-4}$ corresponds to $dV/dr = 100$ km s$^{-1}$ pc$^{-1}$, which is $\sim 30$ times larger than the virial value. Hence, unless one is willing to accept a significantly higher $[^{12}\text{CO}]/\text{H}_2$ abundance ratio, such large values are an indication of a non-virialized gas phase being present in the starburst environment of NGC 1068. A similar situation is described for the starburst nucleus of IC 342 (Irwin & Avery 1992) and the diffuse gas phase of the two-gas-phase model proposed by Aalto et al. (1995) is non-virialized.
5.4.2 A significant non-LTE effect

Previous studies by Aalto et al. (1995) used mainly the ratios $r_{21}$, $R_{10}$ and $r_{21}^{(13)}$ (or equivalently $r_{21}$, $R_{10}$ and $R_{21}$) to deduce a two-component gas phase in starburst nuclei. In section 3.5 we argued that a single gas phase can still account for the average observed line ratios provided that the $^{13}$CO J=1–0 transition is slightly super-thermally excited. The $(n(H_2), \Lambda)$ parameter space where super-thermal excitation of $^{13}$CO J=1–0 occurs becomes significantly wider for higher gas temperatures, comparable to the ones expected in starburst regions ($T_{\text{kin}} \sim 30 - 60$ K). While the exact values of the line ratios in this domain are sensitive to the $(n(H_2), \Lambda)$ assumed, they generally satisfy $r_{21} \sim 0.8 - 1.1$, $r_{21}^{(13)} \sim 1.2 - 2.2$ (hereafter $r_{21}^{(13)}$) and $R_{10} \geq 10$, which covers the range of the average line ratios that Aalto et al. (1995) find for starburst nuclei. This scheme fails completely (i.e., no LVG solution can be found) when $r_{21} < 0.7$.

Observations of the higher transition J=3–2 for $^{12}$CO and $^{13}$CO provide a more sensitive probe to the excitation conditions of the gas and, in the case of the rarer isotope $^{13}$CO, with reduced saturation effects. A thorough search, reveals that the parameter space where the $r_{21}$, $R_{10}$, $R_{21}$ (or equivalently $r_{21}$, $R_{10}$ and $r_{21}^{(13)}$) and the $R_{32}$ (or equivalently $r_{32}^{(13)}$) ratios can be fitted satisfactorily, while $^{13}$CO J=1–0 remains super-thermal, becomes significantly narrower. This conclusion (like the one about the onset of superthermality) is very robust since it depends mainly on the physics of the CO excitation and not on the details of the assumed velocity fields. There is a simple way to demonstrate this from the expression that gives the optical depth of the J+1→J transition, namely

$$\tau_{J+1, J} \propto (J+1) \left[ \frac{N_J}{g_J} - \frac{N_{J+1}}{g_{J+1}} \right]$$

where $N_J$ is the fraction of the total number of molecules at the J level and $g_J = 2J + 1$ is the level degeneracy.

A main feature of super-thermal excitation is to “drain” level J=2 towards level J=1. The last relation shows that a “drain” of the J=2 level towards J=1, which
then becomes overpopulated relative to J=0, causes a decrease of the \( \tau_{10} \) while *simultaneously* increasing \( \tau_{21} \). This can actually lead to \( \tau_{21}/\tau_{10} > 4 \) (the LTE limit), and manifests itself as an increasing \( R_{10} \) and a decreasing \( R_{21} \) with \( R_{10} > R_{21} \). Under such circumstances the value of \( \tau_{32} \) (and hence the value of \( R_{32} \) or \( r_{32}^{(13)} \)) depends sensitively on the degree of the J=3 level excitation. For \( T_{\text{kin}} \geq E_3/k \sim 30 \) K, a gas density of \( n(\text{H}_2) \geq 10^4 \) cm\(^{-3} \) leads to the significant population of the J=3, J=2 levels and an increase of \( \tau_{32} \) such that \( R_{32} \leq R_{21} \). This happens while the J=1-0 can still be super-thermally excited with \( R_{10} > 10 \) and \( R_{10} > R_{21} \).

On the other hand once in the super-thermal regime, the relations \( R_{10} > R_{21} \) and \( R_{21} < R_{32} \) (observed for the global ratios in NGC 1068) can be reproduced for a more restricted range of LVG parameters. This is because the conditions for superthermality (i.e., \( T_{\text{kin}} \geq 20 \) K, \( n(\text{H}_2) \geq 3 \times 10^3 \) cm\(^{-3} \), \( \tau_{10}^{(13)} \leq 0.1 \)) are bounded by the conditions needed to keep a low \( \tau_{32} \) (i.e., a high \( R_{32} \)) which call for a low excitation of the J=3 level; which means \( n(\text{H}_2) < 4 \times 10^4 \) cm\(^{-3} \) and/or \( T_{\text{kin}} < 30 \) K. In the next section we will find that in the two-phase model these non-LTE conditions characterize the diffuse gas phase which has \( \tau_{10} \sim 1 - 2 \) and thus \( \tau_{10}^{(13)} \leq 0.1 \).

### 5.4.3 Parameterization of the two-component model

As already discussed in section 5.2, for abundances \([\text{C}^{18}\text{O}/\text{^{13}CO}] \leq 0.15\), the high values of \( R_{10}^{(18)} \) (and the two values of \( R_{21}^{(18)} \)) measured in NGC 1068 point towards a gas phase with \( \tau_{10}^{(13)} \geq 1 \). This is contrary to the conditions implied by all the other line ratios of \(^{12}\text{CO}, ^{13}\text{CO} \) where \( \tau_{10} \sim 1 - 2 \) and hence \( \tau_{10}^{(13)} \ll 1 \).

We denote as (B) a dense, concentrated gas phase where \(^{13}\text{CO} \) and even \(^{18}\text{O} \) may have substantial optical depths and as (A) a diffuse phase where \( \tau_{10} \sim 1 - 2 \). Then we can express all the observed line ratios as a weighted mean of the corresponding ratios of these gas phases. Hence the \( R_{10}^{(18)} \) line ratio can be expressed as follows:

\[
R_{10}^{(18)} = \frac{R_{10}^{(18)}(A) + [f_c \rho_{13}] R_{10}^{(18)}(B)}{1 + [f_c \rho_{13}]}
\]  

(5.7)

where \( f_c \) is the filling factor of phase (B) relative to phase (A) and \( \rho_{13} = T_R(B)/T_R(A) \).
is the ratio of the $^{13}\text{CO}\ J=1-0$ brightness temperature for the two gas phases.

Because in phase (A) both $^{13}\text{CO}$ and $^{18}\text{O}$ isotopes are optically thin, it follows that $R_{10}^{(18)}(A) = [^{18}\text{O}/^{13}\text{CO}]$, irrespective of their particular excitation conditions (LTE or non-LTE). This stems from the fact that in this phase the $^{13}\text{CO}$, $^{18}\text{O}$ emission is optically thin and therefore the radiative trapping is minimal. Moreover the two isotopes have the same collisional excitation coefficients and are influenced by the same background radiation field resulting in nearly identical level populations. Assuming the highest observed relative abundance inferred for the central regions of the Milky way (see Section 4.2.2) gives $R_{10}^{(18)}(A) = 0.15$.

For the average value of $\langle R_{10}^{(18)} \rangle = 0.3$, equation 5.7 requires that phase (B) must have $R_{10}^{(18)}(B) \geq 0.30$ which means a $^{13}\text{CO} \ J=1-0$ optical depth of $\tau_{10}^{(13)}(B) \geq 2$. This corresponds to a ratio $R_{10}(B) \sim 1$ and the observed $R_{10}$ ratio can be approximated as follows

$$\frac{R_{10}}{\tau_{10}^{(13)}} = \frac{R_{10}(A) + [f^c_{\rho_{13}}]R_{10}(B)}{1 + [f^c_{\rho_{13}}]}$$

(5.8)

From this last relation we see that, for the measured average ratio of $R_{10} = 14$ across the circumnuclear region of NGC 1068, the “brightness contrast” factor $f^c_{\rho_{13}}$ cannot be significantly larger than unity. This is simply because then $R_{10}(A) \geq 30$, which is close to the abundance ratio $[^{12}\text{CO}/^{13}\text{CO}] = 40$ found in galactic nuclear regions. Moreover, in the centers of ultra-luminous IRAS galaxies where the diffuse gas phase (A) is thought to dominate the $R_{10}$ ratio (Aalto et al. 1995) measurements show that $R_{10} \sim 20 - 30$ (e.g., see Table 3.1, NGC 3227, NGC 5135). Hence, for a $f^c_{\rho_{13}} \sim 1$ and the average value $R_{10}^{(18)} \sim 0.3$, Equation 5.7 gives a more realistic lower limit for $R_{10}^{(18)}(B) \geq 0.45$, which corresponds to $\tau_{10}^{(13)} \geq 4$.

Thus, we conclude that if phase (B) is responsible for the observed high $R_{10}^{(18)}$ ratios then this phase has large $^{13}\text{CO}$ optical depths. The resulting large radiative trapping is enough to thermalize the $^{12}\text{CO} \ J=1-0$, 2-1, 3-2 transitions even for low ($n(H_2) \sim 10^2$ cm$^{-3}$) densities and the same $^{13}\text{CO}$ transitions for $n(H_2) \sim 10^3$ cm$^{-3}$. Then the $r_{21}$, $r_{32}$ as well as the $r_{21}^{(13)}$, $r_{32}^{(13)}$ line ratios for gas phase (B) can be estimated.
assuming LTE conditions. This means that for large optical depths these ratios are sensitive only to temperature. Let's proceed now to express $r_{21}$ and $r_{32}$ in the same manner as $R_{10}$, $R_{10}^{(18)}$, namely

$$r_{21} = \frac{r_{21}(A) + [f_c \rho_{12}] r_{21}(B)}{1 + [f_c \rho_{12}]},$$

where $\rho_{12} = T_R(B)/T_R(A)$ denotes the brightness temperature ratio of $^{12}$CO $J=1-0$ for the two gas phases. The two factors $\rho_{13}$ and $\rho_{12}$ are related by the simple relation $\rho_{12} = [R_{10}(B)/R_{10}(A)] \rho_{13}$.

From the last relation it can be shown that $r_{21}$ and $r_{32}$ are dominated by the diffuse gas component. For the optically thick and thermalized phase (B) we have $R_{10}(B) \sim 1$ and $r_{21}(B) \leq 1$, $r_{32}(B) \leq 1$. Furthermore, as we argued earlier, an observed ratio $R_{10} = 14$ means that $R_{10}(A) > 14$, while the upper limit of $R_{10}(A) \leq 30$ requires $f_c \rho_{13} \leq 1$. This yields $f_c \rho_{12} \ll 1$ ($J=1,2$) and therefore $r_{21} \approx r_{21}(A)$, $r_{32} \approx r_{32}(A)$.

This is not the case for the corresponding ratios of the rarer $^{13}$CO isotope. Indeed, since $f_c \rho_{13}$ is not as small as $f_c \rho_{12}$, the observed $r_{32}^{(13)}$ and $r_{21}^{(13)}$ ratios can have a significant contribution from gas phase (B).

$$r_{21}^{(13)} = \frac{r_{21}^{(13)}(A) + [f_c \rho_{13}] r_{21}^{(13)}(B)}{1 + [f_c \rho_{13}]},$$

and

$$r_{32}^{(13)} = \frac{r_{32}^{(13)}(A) + [f_c \rho_{13}] r_{32}^{(13)}(B)}{1 + [f_c \rho_{13}]}.\tag{5.12}$$

We will now proceed to use this simple model to deduce the properties of phase (A) and phase (B) using the measured global ratios. We assume a minimum kinetic temperature of $T_{\text{kin}} = 10$ K for both phases. As we discussed earlier, LTE is a good description for the gas in phase (B), hence the line ratios are defined by $T_{\text{kin}}(B)$ and the $C^{18}$O $J=1-0$ optical depth $\tau^{(18)}$. For phase (A) where non-LTE effects can be important and even prevalent, the line ratios are sensitive to $n(H_2) T_{\text{kin}}$ and $\Lambda$. 

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5.4.4 Results of the modeling

We used a grid of values of \((\tau_{10}^{(18)}, T_{\text{kin}})\) for the gas phase B and equation 5.7 to estimate the “brightness contrast” factor \(f_c\rho_{13}\) by setting \(R_{10}^{(18)}(A) = \left[C^{18}\text{O}/^{13}\text{CO}\right] = 0.15\) and \(R_{10}^{(18)} = 0.30\). Then we used the deduced values of \(R_{10}(A), r_{32}(A), r_{21}(A), r_{21}^{(13)}(A)\) and \(r_{32}^{(13)}(A)\) to constrain the properties of phase (A). The results of this modeling are summarized in Table 5.3.

No acceptable solution was found for \(C^{18}\text{O} J=1-0\) optical depths of \(\tau_{10}^{(18)} \leq 0.4 \Rightarrow R_{10}^{(18)}(B) \leq 0.35\). This is because for an average ratio of \(R_{10}^{(18)} = 0.3,\) the “brightness contrast” factor estimated from Equation 5.7 is \(f_c\rho_{13} \geq 2.8 \Rightarrow R_{10}(A) \geq 53\). This value is larger than the assumed \([^{12}\text{CO}/^{13}\text{CO}]\) abundance and the value \(\sim 30\) which we considered a reasonable upper limit for this ratio. From Table 5.3 it becomes apparent that for values of \(\tau_{10}^{(18)} \geq 1.5\) the estimated line ratios of gas phase (A) become insensitive to \(\tau_{10}^{(18)}\) and \(T_{\text{kin}}(B)\) since the factor \(f_c\rho_{13}\) and hence the contribution of gas phase (B) to the measured line ratios becomes progressively smaller.

A good LVG solution for phase (A) is found only for \(r_{21} = 0.97, r_{32} = 0.74\), corresponding to a \(-30\%\) offset in the BIMA \(^{12}\text{CO}\) intensity. The reason behind this is simple to describe. For a ratio \(r_{21} \leq 0.7\) only low \(T_{\text{kin}}\) and/or sub-thermal excitation conditions are possible. For LTE this gives \(T_{\text{kin}} \leq 6 - 7\) K, which is low for a gas phase that is generated by the violent processes summarized in Section 5.3 which most likely will warm the gas above this limit. Moreover, for such low kinetic temperatures the J=3 level is hardly populated at all and it yields a value for \(r_{32}\) which is too low. This discrepancy becomes more acute for the small/moderate \(^{12}\text{CO} (1-0)\) optical depths expected for gas phase (A). For example, \(\tau_{10} = 1.5\) and \(T_{\text{kin}} = 6\) K give an LTE value of \(r_{32} = 0.2\).

Considering a sub-thermal excitation of the CO emission does not solve this problem either; it actually makes the situation worse. We examined a grid of LVG models for \(r_{21} = 0.68, r_{32} = 0.52\) and \(R_{10} = 15, 20, 25, 30\) (the likely range of this ratio for phase (A)) and no good fit was found that gave both \(r_{21} \sim 0.7\) and \(r_{32} \sim 0.5\) or higher.
Table 5.3  Two component model: The global ratios

<table>
<thead>
<tr>
<th>Gas phase (B)(^a)</th>
<th>Line ratios (A)(^b)</th>
<th>LVG parameters (A)(^c)</th>
<th>Excitation (A)(^e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau_{10}^{(18)}), (f_c\rho_{13}), (T_{\text{kin}})</td>
<td>(r_{21}, r_{32}, R_{10}, R_{21}, R_{32})</td>
<td>(T_{\text{kin}}, n(H_2), \Lambda)</td>
<td>(E_{10}^{(13)}, \tau_{10}^{(12)})</td>
</tr>
<tr>
<td>0.5, 1.35, 15</td>
<td>0.97, 0.74, 32, 15, 31 (1.18, 0.73, 27, 23, 31)</td>
<td>35, 3x10(^3), 1x10(^{-6}) (\chi_{\text{min}} = 1.83)</td>
<td>3.8, 0.29</td>
</tr>
<tr>
<td>0.7, 0.70, 10</td>
<td>0.97, 0.74, 23, 13, 20 (1.05, 0.76, 17, 13, 20)</td>
<td>35, 3x10(^3), 3x10(^{-6}) (\chi_{\text{min}} = 1.80)</td>
<td>2.8, 0.94</td>
</tr>
<tr>
<td>0.9, 0.50, 15</td>
<td>0.97, 0.74, 20, 12, 20 (1.05, 0.76, 17, 13, 20)</td>
<td>35, 3x10(^3), 3x10(^{-6}) (\chi_{\text{min}} = 0.98)</td>
<td>2.8, 0.94</td>
</tr>
<tr>
<td>1.1, 0.40, 20-40</td>
<td>0.97, 0.74, 19, 12, 19 (1.05, 0.76, 17, 13, 20)</td>
<td>35, 3x10(^3), 3x10(^{-6}) (\chi_{\text{min}} = 0.61 - 0.67)</td>
<td>2.8, 0.94</td>
</tr>
<tr>
<td>2.5, 0.25, 15-40</td>
<td>0.97, 0.74, 17, 11, 17-18 (1.05, 0.76, 17, 13, 20)</td>
<td>35, 3x10(^3), 3x10(^{-6}) (\chi_{\text{min}} = 1.1 - 0.9)</td>
<td>2.8, 0.94</td>
</tr>
</tbody>
</table>

\(^a\) The physical conditions of the gas in phase (B): \(\tau_{10}^{(18)}\) is the optical depth of the \(^{18}\)O \(J=1-0\) transition, \(T_{\text{kin}}\) is the kinetic temperature of the gas in Kelvin and \(f_c\rho_{13}\) is the "brightness contrast" factor defined through Equation 5.7.

\(^b\) The line ratios estimated for gas phase (A) (see text), the ones in the parenthesis are the values obtained from the LVG model with the smallest \(\chi^2\).

\(^c\) The LVG parameters that correspond to the best fit of the line ratios of gas phase (A). The units are the same ones used in Table 5.2. The \(\chi_{\text{min}}\) parameter characterizes the goodness of the fit (see Table 5.2).

\(^d\) \(E_{10}^{(13)} = T_{\text{exc}}/T_{\text{kin}}\) for the \(^{13}\)CO \(J=1-0\) transition and \(\tau_{10}\) is the optical depth of the \(^{12}\)CO \(J=1-0\) transition for gas phase (A).
Hence it looks like that the two major ISM phases dominating the CO emission in the circumnuclear starburst region of NGC 1068 are a diffuse phase with density $n(H_2) \sim 10^3$ cm$^{-3}$ and $\tau_{10} \sim 1$, and a more dense phase with $\tau_{10}^{(18)} \sim 1$ (Table 5.3). For completeness we mention that there is another set of LVG solutions that give the second best fit of the line ratios of phase (A) which is not as good as the ones tabulated in Table 5.3. This set corresponds to very warm gas with $T_{\text{kin}} \sim 90 - 120$ K, a density of $n(H_2) = 10^3$ cm$^{-3}$ and $\Lambda = 10^{-5}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$. The LVG-deduced line ratios are $r_{21} = 0.98 - 1.05$, $r_{32} = 0.45 - 0.58$ and $R_{10} = 17 - 20$, $R_{21} = 16 - 17$, $R_{32} = 26 - 27$. From these values it becomes apparent that while $r_{21}$, $r_{32}$ and $R_{10}$ fit the ratios of phase (A) well, the values of $R_{21}$ and especially $R_{32}$ are too high (see Table 5.3). In section 5.5 we will see that this set of solutions becomes more important in the case of an intrinsically high $[^{18}\text{O}/^{13}\text{CO}]$ abundance.

Finally it is interesting to note that the aforementioned range of physical conditions with its high gas kinetic temperatures is characteristic of photon-dominated regions (PDRs) (e.g., Tielens & Hollenbach 1985) where significant quantities of molecules co-exist with atoms and atomic ions. In their description of a two-component gas model Aalto et al. (1995) argue that PDRs are a major and possibly even a dominant constituent of the diffuse gas phase.

### 5.4.5 The dense gas phase

A lower limit for the gas density of phase (B) can be deduced from the information in Table 5.3 and the fact that LTE provides a good description of the excitation of the gas in this phase. The optical depth of the $^{18}\text{O}$ J=1–0 transition can be expressed as follows

$$
\tau_{10}^{(18)} = 1.23 \times 10^4 \left( \frac{1 - e^{-5.26/T_{\text{kin}}}}{T_{\text{kin}}} \right) \left[ \frac{[^{18}\text{O}]}{H_2} \right] n(H_2) \left( \frac{dV}{dr} \right)^{-1}
$$

where $T_{\text{kin}}$ is the kinetic temperature of the gas in (B) phase.

Assuming a virialized “average” cloud for this gas phase means that $dV/dr$ is given by Equation 5.5; hence, for an abundance $[^{18}\text{O}/^{13}\text{CO}] = 10^4$, we get
The very different abundances of $^{12}\text{CO}$ and $^{18}\text{O}$ play a crucial role in making these two isotopes suitable for broadly tracing the two different gas phases described previously. Indeed, it is frequently said that molecules with high dipole moments (e.g., CS, HCN) are needed in order to trace high density gas. However, to a certain extent, rare CO isotopes can do the same. This is because, unlike the high density tracing molecules, $^{12}\text{CO}$ has an abundance high enough for moderate/high optical depth to arise in the general conditions of ISM. The dominant emission of a transition arises in regions where $\tau \geq 1$ and the transition is thermalized. Therefore $^{12}\text{CO}$ J=1-0 can trace a diffuse gas phase since for optical depths of $\tau \sim 1-10$, radiative trapping will thermalize this transition at densities of $n_A(\text{H}_2) = n_{\text{crit}} \times (1 - e^{-\tau}) / \tau \approx 10^2 - 10^3 \text{ cm}^{-3}$, where $n_{\text{crit}} = 2 \times 10^3 \text{ cm}^{-3}$ is the critical density of the J=1-0 transition.

On the other hand, for a much less abundant isotope like $^{18}\text{O}$ where $[^{12}\text{CO}/^{18}\text{O}] = 250 - 500$ (Wannier 1980) an optical depth of $\tau \sim 1$ is usually associated with higher gas densities. Neglecting any differences in excitation between the two isotopes, re-
results in an implied density of the order of \( n_B(H_2) \sim (250-500) \times n_A(H_2) \geq 2 \times 10^4 \text{ cm}^{-3} \) which is more likely to be found in smaller regions with small filling factor deeper in the Giant Molecular clouds.

### 5.4.6 The "low-velocity" line ratios

The global line profiles shown in Figure 5.1 show that the intensity ratio \(^{12}\text{CO}/^{13}\text{CO}\) varies more strongly across the global profile of the \( \text{J}=1-0 \) than the \( \text{J}=2-1, 3-2 \) transitions. Hints of a similar variation are seen in these last two transitions, with larger \(^{12}\text{CO}/^{13}\text{CO}\) intensity ratio at low velocities and smaller at higher velocities, but are much less pronounced. While “missing” \(^{13}\text{CO} \ J=1-0\) flux may contribute to the variation of \( R_{10} \), we explained in section 5.1.1 why we expect such an effect to be minor. However the absolute values of \( R_{10} \) as estimated from the OVRO and BIMA data do have a large uncertainty of \( \sim \pm(30-40)\% \) because of the possible systematic offset in the BIMA \(^{12}\text{CO} \ J=1-0\) and OVRO \(^{13}\text{CO} \ J=1-0\) flux density scale.

In section 5.2 we attributed the differences between the \( \text{J}=1-0 \) and the \( \text{J}=2-1, 3-2 \) transitions to a small/moderate optical depth of \(^{12}\text{CO} \ J=1-0\). From the global spectra in Figure 5.1 we see that the \( R_{10} \) ratio varies by a factor of \( \sim 2 \) across the line profile. For the velocity range of \( V_{\text{LSR}} = 980 - 1050 \text{ km s}^{-1} \) we estimate \( r_{21} = 0.64, r_{32} = 0.42 \) and \( R_{10} = 36 \). Such a high value of \( R_{10} \) requires \( R_{10}(A) \geq 36 \), which is comparable to the assumed abundance \([^{12}\text{CO}/^{13}\text{CO}] = 40\). Moreover, as we already explained (page 103), there is no good LVG solution for these values of the line ratios. The best LVG fit is found for the values that correspond to a \(-30\%\) offset of the \(^{12}\text{CO} \ J=1-0\) intensity. Such an offset also yields a range of BIMA/OVRO-deduced values of \( R_{10} \) that are in better agreement with the independent global measurement reported in Table 5.1.

Applying the \(-30\%\) offset for the \(^{12}\text{CO} \ J=1-0\) intensity for the low velocity range \( V_{\text{LSR}} = 980 - 1050 \text{ km s}^{-1} \) yields the ratios \( r_{21} = 0.91 \pm 0.16, r_{32} = 0.60 \pm 0.08, R_{10} = 25 \pm 3 \). We use these values together with \( R_{21} = 11 \pm 2, R_{32} = 16 \pm 3 \) to constrain the properties of the two-phase model. For the gas phase \((A)\) it must be that \( R_{10}(A) \geq 25 \pm 3 \). We examine a grid of LVG models with \( r_{21}(A) \approx r_{21}, \)
r32(A) \approx r32 	ext{ and } R_{10}(A) = 20, 25, 30, 35. 

We found that the widest set of physical conditions that reproduces the r21(A), r32(A) ratios corresponds to R_{10}(A) = 25, which means \( f_{c \rho_{13}} \ll 1 \), i.e., the gas phase (B) does not contribute significantly to any of the observed line ratios. Including the values of R_{21}, R_{32} in the fit for gas phase (A) yields \( T_{\text{kin}} = 30 \text{ K}, n(H_2) = 3 \times 10^3 \text{ cm}^{-3} \), and \( \Lambda = 10^{-6} \text{ (km s}^{-1} \text{ pc}^{-1})^{-1} \). However, this fit is still not satisfactory since it yields ratios \( R_{21}^{(lvg)} = 23, R_{32}^{(lvg)} = 32 \), which are too large with respect to the ones measured.

This may be an indication that gas phase (A) itself may not be uniform enough to be considered a single phase. Indeed, assuming physical conditions identical to the ones revealed by the aforementioned LVG model but with a contribution \( (f_{c \rho_{13}} = 0.50) \) by a denser component \( (n(H_2) = 3 \times 10^4 \text{ cm}^{-3}) \) with the same \( T_{\text{kin}} \) and \( \Lambda \) one can reproduce the line ratios for this velocity range rather well. This additional gas phase still has a moderate \( ^{12}\text{CO} \ J=1-0 \) optical depth \( (\tau_{10} \sim 2) \) and a slightly super-thermal \( ^{13}\text{CO} \ J=1-0 \) transition.

The "low-velocity" CO emission corresponds to the Giant Molecular Associations (GMAs) found in the easternmost part of the circumnuclear starburst region of NGC 1068. Thus we conclude that, on average, these associations are dominated by the diffuse gas phase (A), while the more dense and optically thick phase (B) does not contribute significantly to either the \( ^{12}\text{CO} \) or \( ^{13}\text{CO} \) emission.

5.4.7 The "high-velocity" line ratios

For the high velocity interval of \( V_{\text{LSR}} = 1200 - 1280 \text{ km s}^{-1} \), we estimate the ratios \( r_{21} = 1.1 \pm 0.2, r_{32} = 0.93 \pm 0.13, R_{10} = 13 \pm 2 \text{ and } R_{21} = 9 \pm 2, R_{32} = 15 \pm 3. \)

Single gas phase LVG modeling gives \( T_{\text{kin}} = 20 \text{ K}, n(H_2) = 10^4 \text{ cm}^{-3} \) and \( \Lambda = 10^{-6} \text{ (km s}^{-1} \text{ pc}^{-1})^{-1} \). These conditions are identical to the ones found from the best LVG model of the global ratios in Table 5.2. From this table, we can see that all the above ratios are well reproduced by the model and only the value of \( r_{32}^{(lvg)} = 0.75 \) is somewhat lower than the measured one but they are still broadly consistent within the range of the thermal error. A two-component analysis of the line ratios at the high velocity interval gives \( T_{\text{kin}}(B) > 20 \text{ K} \) and \( f_{c \rho_{13}} = 0.4 - 0.5 \) which, for \( R_{10}^{(lvg)} = 0.30, \)
corresponds to $\tau_{10}^{(18)} \sim 1$. The corresponding conditions for the gas phase (A) are $T_{\text{kin}} = 40$ K, $n(\text{H}_2) = 3 \times 10^3$ cm$^{-3}$ and $\Lambda = 3 \times 10^{-6}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$.

The "high-velocity" CO emission originates from the westernmost part of the circumnuclear starburst region of NGC 1068. More specifically this emission is dominated by the most massive (Planeras, Scoville & Myers 1991) Giant Molecular Association (GMA) in NGC 1068, which resides in the southwestern part of the circumnuclear region. This GMA is easily discernible in the $^{12}$CO J=1–0 (Planeras, Scoville & Myers 1991; Helfer & Blitz 1995) and $^{13}$CO J=1–0 (Figure 4.1) interferometric maps, and is centered at $(\Delta \alpha, \Delta \delta) \approx (-8'', -15'')$. Distinct emission from this region can also be seen in the lower resolution $^{13}$CO J=2–1, 3–2 maps (Figures 4.10 4.11).

From the previous analysis, it seems that the CO emission from this part of the galaxy has a significant contribution from the dense and optically thick gas phase (B). This notion is supported by a high sensitivity map of HCN J=1–0 made with the IRAM interferometer (Tacconi et al. 1994) at a resolution of $\sim 4'' \times 3''$. This map shows that, apart from the Seyfert nucleus itself, the brightest HCN emission originates from the western part of the circumnuclear region of NGC 1068 and is most prominent towards the location of the massive GMA at $(\Delta \alpha, \Delta \delta) \approx (-8'', -15'')$. Since the HCN J=1–0 emission arises in denser ($n(\text{H}_2) > 10^4$ cm$^{-3}$) regions it follows that such regions are mostly located in the GMAs in the western part of the galaxy.

5.5 The changing physical conditions of the gas in NGC 1068: Summary

We used the line ratios estimated for the two extreme velocity ranges of the CO emission in order to deduce the associated physical properties of the gas. High resolution interferometric maps demonstrate that the CO emission at the "low-velocity" ($V_{\text{LSR}} = 980 - 1050$ km s$^{-1}$) and the "high-velocity" ($V_{\text{LSR}} = 1200 - 1280$ km s$^{-1}$) range is dominated by the GMAs that lie in the easternmost and the westernmost part of the starbursting circumnuclear region of NGC 1068 respectively.
We find that the warm, diffuse gas phase (A) with \( \tau_{10} \sim 1 - 2 \) dominates the average \(^{12}\text{CO}\) and \(^{13}\text{CO}\) emission arising from the eastern GMAs with negligible contribution from the more dense, optically thick gas phase (B). A typical set of conditions found is \( T_{\text{kin}} = 30 \text{ K}, n(\text{H}_2) = 3 \times 10^3 \text{ cm}^{-3} \), and \( \Lambda = 10^{-6} \) (km s\(^{-1}\) pc\(^{-1}\))\(^{-1}\). Nevertheless we also find that a homogeneous phase (A) fails to fit all the line ratios (most notably \( R_{21} \) and \( R_{32} \)) and a denser component \( (n(\text{H}_2) = 10^4 \text{ cm}^{-3}) \) with similar \( T_{\text{kin}} \) and \( \Lambda \) may be present. This component still has a moderate \(^{12}\text{CO} J=1-0 \) optical depth of \( \tau_{10} \sim 2 \).

On the other hand, the optically thick and dense phase (B) seems to have a significant contribution in the GMAs that are located in the western part of the circumnuclear CO emission. A two-phase modeling yields \( T_{\text{kin}}(B) > 20 \text{ K} \) and \( f_{\text{e}} \rho_{13} = 0.4 - 0.5 \), while for phase (A) the corresponding conditions are \( T_{\text{kin}} = 40 \text{ K}, n(\text{H}_2) = 3 \times 10^3 \text{ cm}^{-3} \) and \( \Lambda = 3 \times 10^{-6} \) (km s\(^{-1}\) pc\(^{-1}\))\(^{-1}\).

It is worth noting that hints of the wide range of physical conditions of the molecular gas in NGC 1068 can be revealed by using only the \( r_{32} \) and \( R_{10} \) ratios and simple one-phase LVG modeling. Apart from the fact that both these ratios are sensitive to the gas excitation conditions, they are also the ones that can be estimated at the highest possible resolution (\( \sim 16'' \)) with the current data set. This allows the spatial separation of some of the regions with different physical conditions.

The measured range of \( r_{32} \sim 0.4 - 0.8 \) towards the various GMAs (Fig. 4.8), and the fact that in most of them we measure \( R_{10} \geq 10 \) with \( \langle R_{10} \rangle = 14 \) yields \( T_{\text{kin}} \geq 20 \text{K}, n(\text{H}_2) = 10^3 - 10^4 \text{ cm}^{-3} \) and \( \Lambda = 10^{-5} - 10^{-6} \) (km s\(^{-1}\) pc\(^{-1}\))\(^{-1}\). For \( r_{32} = 0.57 - 1.1 \) (\( \sim 30\% \) offset for \(^{12}\text{CO} J=1-0 \)) the range of the inferred gas conditions becomes even wider. In all cases one finds that the most dense gas lies towards the locations of the large GMAs in the western part of the circumnuclear emission.

For example, high values of \( r_{32} \) (Fig. 4.8) and low values of \( R_{10} \) are found towards the massive molecular complex in the southwestern part of the circumnuclear emission as seen in \(^{12}\text{CO} J=1-0 \) (Planesas et al. 1991; Helfer & Blitz 1995) and \(^{13}\text{CO} J=1-0 \) interferometric maps. A single-phase LVG analysis of the \(^{12}\text{CO}, ^{13}\text{CO} \) transitions suggests the presence of warm gas with \( T_{\text{kin}} = 30 \text{ K}, \tau_{10} \sim 2 \) and \( n(\text{H}_2) = 3 \times 10^4 \text{ cm}^{-3} \).
5.6 The case for a high $[\text{C}^{18}\text{O}/^{13}\text{CO}]$ abundance

We used the $[\text{C}^{18}\text{O}/^{13}\text{CO}] = 0.15$ abundance ratio throughout the present study. As we have already demonstrated (section 5.4.3) deducing the properties of the molecular gas, and especially those of the dense, optically thick gas phase (B), depends on the assumed $[\text{C}^{18}\text{O}/^{13}\text{CO}]$ abundance ratio. Hence it will be instructive to examine some of the implications of a higher value of this ratio for the deduced properties of the gas.

It is easy to see that for $[\text{C}^{18}\text{O}/^{13}\text{CO}] \sim 0.30$ the single-phase LVG solution reported in Table 5.2 can fit all the global ratios (Table 5.1) including $R_{10}^{(18)}$ and $R_{21}^{(18)}$. Such high $[\text{C}^{18}\text{O}/^{13}\text{CO}]$ abundances may be implied from multi-line studies of starburst regions by Henkel & Mauersberger (1993) who observed various isotopic species of CO, CN, CS, HCO$^+$. They find isotopic ratios of $^{12}\text{C}/^{13}\text{C} \sim 40-50$ and an "over-abundance" of $^{18}\text{O}$ with respect to $^{17}\text{O}$ and $^{16}\text{O}$, which they interpret as a result of nucleosynthesis by the massive stars of a top-heavy initial mass function.

An abundance of $[\text{C}^{18}\text{O}/^{13}\text{CO}] \sim 0.30$ can naturally account for the high average $I(\text{C}^{18}\text{O})/I(\text{^{13}CO})$ $J=1-0$ intensity ratio observed with OVRO (section 4.2.2). In section 4.2.2 we argued though that such a solution still has the problem of accounting for the large variations of this intensity ratio among the various GMAs. In the case of a high $[\text{C}^{18}\text{O}/^{13}\text{CO}]$ abundance, smaller values of the $^{13}\text{CO}$ $J=1-0$ optical depth are needed to reproduce the observed variations of $I(\text{C}^{18}\text{O})/I(\text{^{13}CO})$. Nevertheless, these values can be high enough that the implied $\tau_{10}^{(13)}$ optical depth yields rather low $R_{10}$ ratios. For example, $R_{10}^{(18)} = 0.4 \Rightarrow \tau_{10}^{(13)} \sim 1$, which in turn gives $R_{10} = 1.6$ (LTE assumed). In our high resolution maps (Section 4.2.2) we routinely find values as high as $R_{10}^{(18)} \sim 0.4$ or higher, but never measure $R_{10}$ as small as $R_{10} \sim 1 - 2$.

This points again towards different gas components dominating the $^{12}\text{CO}$ and $^{13}\text{CO}$ emission. Hence it worths exploring the properties of a two-phase gas model, even though one is no longer strictly necessary to account for the global line ratios.

Since the average ratio $R_{10}^{(18)} = [\text{C}^{18}\text{O}/^{13}\text{CO}] \sim 0.30$, the "brightness temperature" contrast factor $f_{c\rho_{13}}$ is no longer constrained by Equation 5.7. This means that, on average, phase (B) may have significantly smaller optical depth for $^{13}\text{CO}$ and $\text{C}^{18}\text{O}$.
J=1–0 than inferred in our previous two-component model analysis.

We still assume that the gas phase (B) describes gas more concentrated and optically thick than the gas in phase (A) and with $T_{\text{kin}}(B) \leq T_{\text{kin}}(A)$. Moreover we assume that LTE conditions prevail in phase (B) and hence all the associated line ratios are functions only of the kinetic temperature and optical depth. For this phase we examined a grid of models with optical depths of $\tau_{10}^{(13)}(B) = 0.07–1.1$ (with $\Delta \tau = 0.2$), $\tau_{10}^{(13)}(B) = 1.1, 1.5, 2, 4$ and kinetic temperatures of $T_{\text{kin}}(B) = 10, 15, 20, 30, 40 \text{ K}$.

We find a good fit for a gas phase (A) with $T_{\text{kin}} = 30 – 35 \text{ K}$, $n(\text{H}_2) = 10^3 \text{ cm}^{-3}$ and $\Lambda = 3 \times 10^{-6} \text{ (km s}^{-1} \text{ pc}^{-1})^{-1}$, which is identical to the LVG solution found in the previous section. However, unlike the case where $[\text{C}^{18}\text{O}/^{13}\text{CO}] = 0.15$, we now find that on many occasions the “warm gas” solution with $T_{\text{kin}} = 90 – 120 \text{ K}$, $n(\text{H}_2) = 10^3 \text{ cm}^{-3}$ and $\Lambda = 10^{-6} \text{ (km s}^{-1} \text{ pc}^{-1})^{-1}$ reproduces the line ratios of phase (A) equally well or better. This is because a moderate $\tau_{10}^{(13)}(B)$ yields larger $r_{21}^{(13)}(B)$ and $r_{32}^{(13)}(B)$, and for a given $f_c \rho_{13}$ factor, these correspond to smaller $r_{21}^{(13)}(A)$ and $r_{32}^{(13)}(A)$ ratios that can be more easily reproduced by the “warm gas” solution.

In all the cases where a good fit is found the $^{12}\text{CO}$ emission is dominated by the diffuse gas phase (i.e., $f_c \rho_{12} \ll 1$), while the “brightness contrast” factor for $^{13}\text{CO}$ $J=1–0$ optical depths for which a good fit is found is $\tau_{10}^{(13)}(B) \geq 0.5$. The range of $^{13}\text{CO}$ $J=1–0$ optical depths can still be fitted but over a narrower range of $T_{\text{kin}}(B)$. As expected, for $\tau_{10}^{(13)}(B) > 1$, the fit is no longer sensitive to the values of $\tau_{10}^{(13)}(B)$ and it remains sensitive only to $T_{\text{kin}}(B)$, as long as it is $\leq 30 \text{ K}$. A typical set of conditions for phase (B) are $\tau_{10}^{(13)}(B) = 0.9$ and $T_{\text{kin}}(B) = 10 – 20 \text{ K}$.

The fact that in this case phase (B) is characterized by $\tau_{10}^{(13)} \sim 1$ rather than $\tau_{10}^{(18)} \sim 1$ makes the lower limit of the gas density estimated by Equation 5.14 smaller by a factor $[\text{C}^{18}\text{O}/^{13}\text{CO}]^2 = 0.09$. This simply states the fact that for a given $T_{\text{kin}}$ and virialized velocity field, the more abundant isotope $^{13}\text{CO}$ will become optically thick and thermalized at a lower gas density than the rarer $^{18}\text{O}$.
5.7 Molecular gas mass in NGC 1068

In this final section we will estimate the molecular gas content in the circumnuclear region of NGC 1068 and explore the influence of the physical state of the gas on the inferred masses. In order to do that we will use four methods that use progressively more information about the molecular gas excitation and compare their results.

The first method is simply the use of the standard galactic conversion factor and the value we use here is

\[
X_G = \frac{M(H_2)}{L_{CO}} = 5.0 \text{ M}_\odot (\text{km s}^{-1} \text{ pc}^2)^{-1}
\]  

(5.15)

adopted by Solomon & Barrett (1991), where the $^{12}$CO J=1–0 luminosity $L_{CO}$ is estimated from

\[
L_{CO} = A_s \int_{\Delta v} \int_{A_s} T_b(a, \nu) \, da \, d\nu = \Omega_c \, D^2 \int_{\Delta v} T_{MB}^{(G)}(\nu) \, d\nu
\]  

(5.16)

where $T_{MB}^{(G)}(\nu)$ is the area-averaged spectrum defined in Equation 5.1, $\Omega_c$ is the solid angle corresponding to the averaging area and $D$ is the distance to the galaxy (see Table 4.1).

The velocity-integrated brightness of $^{12}$CO J=1–0 from the Kaneko et al. (1989), Maiolino et al. (1997) and our measurement (scaled by −30%) give an average of $I = 88 \text{ K km s}^{-1}$, over a circle with $R \sim 1'$. Using $X_G$ then gives $M(H_2) \approx 6 \times 10^9 \text{ M}_\odot$.

The second method takes into account the fact that, under certain assumptions, the conversion factor $X$ depends on the average gas density $\langle n(H_2) \rangle$ and the brightness temperature $T_b$ of the $^{12}$CO J=1–0 transition as follows

\[
X = 2.1 \sqrt{\frac{\langle n(H_2) \rangle}{\langle T_b \rangle}}
\]  

(5.17)

The above expression is the simplified version of the equation given by Bryant & Scoville (1996) and it allows a first order correction of the factor $X$ by taking into account differences in the average density and brightness temperature of the gas. From our single-component LVG analysis (see Table 5.2) we find that $X/X_G \approx 1 - 3$, which
is within the range of the expected uncertainties. Studies of warm cloud cores like Orion-KL, M17SW and W3(OH) (Young & Scoville 1982) find $X/X_G \sim 4 - 7$. Hence a higher value of $X$ may be more appropriate for the starburst region of NGC 1068, since such type of clouds will significantly contribute to the observed CO emission. This of course assumes that the assumptions that lie behind the application of $X$ are valid for such molecular clouds.

There are several studies (Dickman et al. 1986; Maloney & Black 1988; Bryant & Scoville 1996) that attempt to quantify the effects of the molecular gas environment on the value of $X$, especially when the $^{12}$CO emission is optically thick. Two principal effects are due to (a) the presence of a non-virialized gas component and, (b) the shadowing of molecular clouds in spatial and/or velocity space. In the first case the factor $X$ as expressed by Equation 5.17 will overestimate the amount of molecular gas mass, while in the second case it will underestimate the mass. Aside from situations where the angular resolution is high enough to resolve individual clouds, cloud-cloud shadowing may be important only towards quiescent cloud environments unlike the ones expected in a nuclear starburst. Therefore the sole most important factor affecting $X$ is the presence of a non-virialized gas component where cloud linewidths are no longer good gas mass indicators.

The third method is based on the possibility that $^{12}$CO and even more so $^{13}$CO may have moderate/small optical depths throughout the volume of the emitting gas. It can be easily shown that the total number of CO molecules on the energy level $J$ is given by the expression

$$N_J = \frac{8\pi k v_{J,J-1}^2}{hc^3 A_{J,J-1}} \beta_{J,J-1}^{-1} L_{CO}(J, J - 1)$$  \hspace{1cm} (5.18)$$

where $A_{J,J-1}$ and $\beta_{J,J-1}$ are the Einstein coefficient and the escape probability of the $J \rightarrow J - 1$ transition respectively, while $L_{CO}(J, J - 1)$ is the corresponding luminosity (see Equation 5.16).

A good approximation of the total $H_2$ mass is then provided by the expression
\[ M(H_2) = X_{\text{CO}} (N_1 + N_2 + N_3) \mu m_{H_2} \]  

where \( X_{\text{CO}} \) is the abundance of \( H_2 \) relative to the particular CO isotope and \( \mu m_{H_2} \) is the mean mass per \( H_2 \) molecule.

After substituting \( N_1, N_2, N_3 \) from Equation 5.18 we get

\[
X = \frac{8\pi k \mu m_{H_2}}{hc^3} \left( \frac{\nu_{10}^2}{A_{10}} \right) \left[ 1 + \left( \frac{\nu_{21}}{\nu_{10}} \right)^2 \frac{A_{10}}{A_{21}} \frac{\beta_{10}}{\beta_{21}} r_{21} + \left( \frac{\nu_{32}}{\nu_{10}} \right)^2 \frac{A_{10}}{A_{32}} \frac{\beta_{10}}{\beta_{32}} r_{32} \right] \beta_{10}^{-1} X_{\text{CO}} \]  

(5.20)

where \( r_{j+1,j} = L_{\text{CO}} (J + 1, J)/L_{\text{CO}} (1, 0) \).

The advantage of this approach is that in the optically thin case, where \( \beta_{J,J-1} \sim 1 \), the last expression is totally independent of the particular excitation conditions and the details of the gas velocity field that determine the value of \( \beta_{J+1,J} \). Moreover, the assumption about the virialization of the average molecular cloud needed to deduce \( X \) (Equation 5.17) is no longer necessary. The omission of \( N_0 \) and \( N_J > 3 \) is not expected to have a major effect on the value of \( M(H_2) \) for the average gas density and temperature expected in molecular clouds. This is suggested by a study of Giant Molecular Cloud (GMC) cores done by Goldsmith et al. (1997). They find good agreement between the virial mass and the mass deduced using observations of the \( C^{18}O \) isotope and Equation 5.20. They also explore the accuracy of this method over a wide range of physical conditions and find that the true mass can be at most \( \sim 2 \) times larger than the one computed from Equation 5.20. This occurs for cold (\( T_{\text{kin}} \approx 10 \) K) and diffuse (\( n(H_2) < 10^3 \) cm\(^{-3} \)) gas where the term \( N_0 \) becomes important, or warm (\( T_{\text{kin}} > 50 \) K) and dense (\( n(H_2) > 10^5 \) cm\(^{-3} \)) gas where levels above \( J=3 \) become significantly populated.

Of course in the optically thick case the intricacies of the molecular gas excitation become much more important and detailed modeling is needed in order to estimate the escape probabilities \( \beta_{J+1,J} \) that appear in Equation 5.3. Expressing this equation in astrophysical units gives
\[ X = 0.078[r] \left[ 1 + 0.42 \left( \frac{\beta_{10}}{\beta_{21}} \right) r_{21} + 0.26 \left( \frac{\beta_{10}}{\beta_{32}} \right) r_{32} \right] \beta_{10}^{-1} \]  

(5.21)

where we assumed \([\text{H}_2/\text{^{12}CO}] = 10^4\) and \([r] = [\text{^{12}CO}/x\text{C}_\text{O}]\) is the abundance of \(^{12}\text{CO}\) relative to the isotope used.

Applying this method for \(^{12}\text{CO}\) and using the results from Table 5.2 to estimate the average escape probabilities we find a maximum value for \(X\) that is \(X \approx 0.4\), or \(X_G/X \sim 12\). Using the more optically thin \(^{13}\text{CO}\) isotope instead yields a conversion factor of \(X(^{13}\text{CO}) \approx 5 - 6\), which gives a similar estimate of \(M(\text{H}_2)\) as the previous one. The global gas mass estimated from these methods is \(M(\text{H}_2) \approx 5 \times 10^8 \, M_\odot\).

As discussed earlier Equation 5.21 gives a lower limit of the total gas mass and taking into account the population of all the energy levels can result in a gas mass that is at most \(\sim 2\) times larger. This still leaves the \(M(\text{H}_2)\) estimated with this method \(\approx 6\) times smaller than the one found from the standard galactic conversion factor. In Section 4.2 we found a similar discrepancy between the molecular gas surface density estimated from \(^{12}\text{CO}\) and \(^{13}\text{CO}\) J=1-0 interferometric maps. In that case the standard galactic conversion factor yields higher surface densities than the ones deduced from the \(^{13}\text{CO}\) J=1-0 brightness (assuming LTE). Two effects that may contribute to this difference in the estimated gas mass are, a) the presence of a non-virialized gas component and, b) a large optical depth of the particular CO isotope.

The first effect will lead to an overestimate of the molecular gas mass whenever a factor that converts \(^{12}\text{CO}\) integrated line luminosity to gas mass is used. This is because the line width of the CO emission from the “average” cloud is now larger than the virial one. In such a case modifying the standard conversion factor only in terms of the average gas density and brightness temperature (Equation 5.17) is not enough. An additional modification is needed (see e.g., Bryant & Scoville 1996), which yields a smaller \(X\) factor, to account for the non-gravitational part of the CO linewidth. Our analysis using a two-phase model for the gas indicates that such a molecular gas component is indeed present.
The second effect has to do with the fact that in an optically thick medium a significant amount of gas mass can have only a small contribution to the total observed luminosity. This is straightforward to understand in the case where the line formation mechanism in molecular clouds is local. Then the observed line emission comes from the outer layer of the cloud where $\tau \sim 1 - 3$ and thus a lot of gas mass can "hide" in its interior. The $\beta_{J,J'}$'s factors can, to a certain extent, correct for this effect but obviously this correction becomes increasingly unreliable the larger the optical depth.

However in the case where large scale systematic motions within each cloud (and among the various clouds themselves) are present, the various optically thick components appear centered at different velocities along the total line profile and hence are in principle visible. In such a situation significant gas mass can still "hide" provided that the more optically thick component has a lower temperature, a smaller velocity gradient and overall volume than the external, more diffuse gas component. This is exactly the type of molecular gas differentiation found for the gas in NGC 1068 and generally in starburst nuclei. A combination of a small spatial/velocity filling factor and a lower average temperature can reduce the luminosity contribution of the optically thick gas phase to $\leq 0.1\%$ of the luminosity of the diffuse, warmer gas component that has an equal amount of gas mass. We must mention here that even in the case of a large velocity gradient it can be easily demonstrated that a significant portion of gas mass can still be contained (without significantly contributing to the luminosity) within the small molecular cores where the line width formation mechanism becomes local again, i.e., the linewidth is thermal with a small contribution from turbulence or any other type of large scale motions.

Our study of the molecular gas as a two-component gas phase allows us to examine the amount of mass contained in the optically thick and concentrated gas phase (B) and the more diffuse and optically thick phase (A). Assuming that phase (B) is characterized by moderate $^{18}$O $J=1-0$ optical depth and phase (A) by moderate $^{12}$CO $J=1-0$ optical depth (see Table 5.3), we compute the relative gas mass in the two phases to be given by the expression
\[
\frac{M_B}{M_A} = 0.13 \left( \frac{\rho_{13}}{\rho_{18}} \right) \left( \frac{13\text{CO}}{18\text{O}} \right) \frac{\left( T_{\text{kin}} \frac{e^{5.26/T_{\text{kin}}}}{1 + 0.42 r^{(13)}_{21} + 0.26 r^{(13)}_{32}} \right) \beta_{10}^{-1}}{R^{(18)}_{10}} (B) \]

where \( T_{\text{kin}} \) and \( \beta_{10} \) are the average kinetic temperature and escape probability in gas phase (B) and \( r^{(13)}_{21} \) and \( r^{(13)}_{32} \) are the line ratios for \(^{13}\text{CO}\) in phase (A).

The last equation is derived after assuming LTE conditions for phase (B) and employing Equation 5.21 to estimate the gas mass in phase (A) using the optically thin isotope \(^{13}\text{CO}\). The molecular gas density and temperature (Table 5.3) of phase (A) as well as the fact that \(^{13}\text{CO}\) is optically thin ensures that the \( M_A \) computed using Equation 5.21 indeed estimates most of the gas mass of this phase. After substituting values from Table 5.3 we obtain \( M_B/M_A \approx 5 - 10 \) suggesting that most of the mass resides in the dense, optically thick gas phase (B). The estimated total gas mass is \( M(\text{H}_2) = (1 + M_B/M_A) M_A \approx 3 \times 10^9 \, \text{M}_\odot \).

As expected this mass estimate is larger than the one found from Equation 5.21 under the assumption of optically thin \(^{13}\text{CO}\) emission, yet smaller than the ones computed from the standard galactic conversion factor (Equations 5.15, 5.17) that uses the \(^{12}\text{CO} \, \text{J}=1-0\) line luminosity. This remaining difference occurs because the \(^{12}\text{CO} \, \text{J}=1-0\) line emission is dominated by a non-virialized diffuse gas component.

### 5.7.1 Molecular gas estimates of individual GMAs

It is now clearer why the gas surface density estimated from high resolution \(^{12}\text{CO} \, \text{J}=1-0\) maps with the use of the standard galactic conversion factor is higher than the one found from the brightness of our \(^{13}\text{CO} \, \text{J}=1-0\) map and the assumption of LTE. This discrepancy can now be understood in terms of a non-virialized component dominating the \(^{12}\text{CO}\) emission, hence making the \(^{12}\text{CO} \, \text{J}=1-0\) integrated line brightness an unreliable gas mass tracer, and an optically thick and more dense component dominating the \(^{13}\text{CO}, \, 1^8\text{O}\) emission. Moreover, the fact that the diffuse, non-virialized component has a small/moderate \(^{12}\text{CO} \, \text{J}=1-0\) optical depth makes this transition particularly sensitive to the ambient physical conditions. This can result in variations of its brightness that are unrelated to mass content.
Excitation conditions of the molecular gas indeed vary spatially as revealed by our analysis in section 5.4.1 and expected from the distribution of the “hot spots” of star formation seen in Hα maps (Delgado et al. 1997). Moreover the C^{18}O isotope and to some extent 13CO seem to trace a different, significantly more optically thick and dense component that may contain most of the gas mass. From this point of view it is instructive to note that the C^{18}O J=1–0 brightness of individual GMAs (see Figure 4.3) does not smoothly trace the 13CO J=1–0 (Figure 4.2) or the 12CO J=1–0 (Planesas et al. 1991, Helfer & Blitz 1995) brightness. In many locations the C^{18}O J=1–0 appears significantly brighter with 12CO J=1–0 maintaining the same average brightness and 13CO J=1–0 varying but not as strongly.

This means that in starburst environments the brightness of the most commonly used transition 12CO J=1–0 may not accurately reflect molecular gas surface density to the degree that allows meaningful comparisons of the mass among various GMAs.

Nevertheless, using the 12CO J=1–0 luminosity as a relative mass indicator may still be viable on larger scales (≥ 0.5 kpc), even in starburst environments. This may be the case simply because spatial averaging over large scales can “smooth” the local peculiarities of the CO excitation in phase (A) and the M_B/M_A ratio. Then, even though 12CO J=1–0 luminosity is dominated by the diffuse gas component (A), it can still provide a way to compare gas mass among the various parts of the galaxy. For example the large GMA located at the southwestern part of the circumnuclear region dominating the global line profile at high velocities seems to have both high 12CO J=1–0 peak brightness temperatures in high resolution maps (Planesas, Scoville & Myers 1991; Helfer & Blitz 1995) and a significant contribution from gas phase (B), the most massive of the two gas phases.
5.8 Molecular gas in NGC 1068: Conclusions

We conducted an extensive set of observations in order to map the distribution of the molecular gas in the inner $\sim 1' \times 1'$ of the archetypal Seyfert 2/starburst galaxy NGC 1068. We made fully sampled maps of $^{12}$CO, $^{13}$CO $J=2-1$, $3-2$ transitions and combined them with a $^{12}$CO $J=1-0$ map which we convolved to the same resolution. Finally we obtained high resolution $^{13}$CO, $^{18}$O $J=1-0$ interferometric maps and two low resolution test spectra of the $^{18}$O $J=2-1$ transition. Our main conclusions can be summarized as follows:

1. We find that the average conditions of the molecular gas can be described by a dense gas phase with $n$(H$_2$) = $10^4$ cm$^{-3}$, a temperature of $T_{\text{kin}} = 20$ K and moderate optical depth $\tau_{10} \sim 1 - 2$ for the $^{12}$CO $J=1-0$ transition. However a single gas phase with such a moderate $^{12}$CO $J=1-0$ optical depth cannot reproduce the high $^{18}$O/$^{13}$CO $J=1-0$ intensity ratio and its large spatial variations observed in interferometric maps.

2. A simple two-component model is used to describe the state of the “average” molecular cloud in the starburst environment on NGC 1068. We find that this model can account for all the observed line ratios and their variation across the galaxy. It consists of a dense ($n$(H$_2$) $\geq 10^4$ cm$^{-3}$), more spatially concentrated component where $^{18}$O $J=1-0$ has a moderate optical depth ($\tau_{10}^{(18)} \sim 1$), surrounded by a more diffuse ($n$(H$_2$) = $10^3$ cm$^{-3}$), warmer gas phase where $^{12}$CO $J=1-0$ has $\tau_{10} \sim 1 - 2$.

3. Our analysis shows that the dense and optically thick component contains most of the gas mass, while the more diffuse component dominates the observed $^{12}$CO emission and is probably not virialized. This leads to an overestimate of molecular gas mass when the luminosity of the $^{12}$CO $J=1-0$ line and a standard galactic conversion factor are used, and an underestimate when transitions of the $^{13}$CO isotope are used under the assumption that they have small/moderate optical depth. Moreover the variations of the $^{12}$CO $J=1-0$ brightness over small scales can be the result of varying excitation conditions of this diffuse gas phase rather than the result of varying gas surface densities.
Chapter 6

General conclusions and future work

The purpose of this work was to examine the state of the molecular gas in the host galaxies of Seyfert nuclei. Previous work suggested that global properties like Far Infrared luminosity and CO luminosity over scales of kiloparsecs seemed to correlate with Seyfert type, with type 2 being more luminous than type 1. A straightforward interpretation of this is that Seyfert 2 galaxies have a higher star formation rate and molecular gas mass than Seyfert 1. This is difficult to understand if the only difference between the two types of Seyferts arises from the orientation of a molecular torus with size of $L \leq 10$ pc that either obscures the active nucleus (Seyfert 2) or it does not (Seyfert 1).

An enhanced star forming activity in Seyfert 2 galaxies will heat and disrupt the molecular gas present and thus one would expect this to be discernible in the line ratios of CO and its isotopes over large scales. Equally important is the possibility that the larger CO luminosity of type 2 with respect to type 1 Seyferts and quiescent spirals simply reflects a higher degree of molecular gas excitation rather than larger amounts of gas mass.

In our study we found that no significant difference in the global excitation of the molecular gas between Seyfert 1 and Seyfert 2 galaxies can be discerned from the line ratios of the $^{12}$CO J=2–1, 1–0 and $^{13}$CO J=1–0, 2–1 transitions. However,
in the same work we show that comparing line ratios that average over large areas of a galaxy may not reveal the differences in the gas excitation if these occur in the more confined area of a starburst nucleus. Such practices have been used in the past, especially for distant active galaxies, where even high resolution measurements of the CO lines still sample gas over a large area of the galaxy. In such cases even very FIR-luminous starbursting galaxies like IC 5135 and NGC 7469 may appear to be harboring cold and/or sub-thermally excited gas. Hence, in such cases, analysis of CO lines will not yield any useful insight about the molecular gas excitation in the central regions of the galaxy, where the starburst is expected influence the average physical conditions of the gas.

A meaningful comparison of the global gas excitation conditions in galaxies with varying degrees of activity can still be made provided that the same average galactic area is sampled by the telescope beam. From our study and relevant data in the literature we find that Seyferts as a class seem to harbor warm gas in the nucleus over scales of $\sim 0.5 - 1$ kpc, i.e., similar to the scales associated with starburst nuclei. This is consistent with the notion that Seyfert 2 (the most numerous type of Seyferts) are more likely to harbor a central starburst than Seyfert 1 and field spirals.

In this picture the molecular gas is efficiently driven towards the nuclear region where it "fuels" a starburst as well as the Active Galactic Nucleus (AGN). If this "fueling" process remains effective over scales ranging from $L \sim 1$ kpc down to a few parsecs and occurs more often in Seyfert 2 galaxies it can naturally explain why the onset of a central starburst is linked with a higher probability of obscuring the AGN. Recent studies suggest that type 2 Seyferts exhibit asymmetric morphologies and signs of past interactions more often than type 1 or field spirals, and interactions are known to foster efficient gas mass transport to the inner regions, where it can "ignite" a starburst and "fuel" a supermassive black hole.

However, in this picture a systematically higher global molecular gas mass reservoir in type 2 with respect to type 1 Seyferts, if true, would still be difficult to interpret. While more recent statistical studies show that this may not be the case, our study of NGC 1068 demonstrates that the use of the standard method of finding
molecular gas mass from the $^{12}$CO J=1–0 luminosity can significantly overestimate the gas mass present in starburst environments. More specifically higher CO luminosities of Seyfert 2 with respect to Seyfert 1 galaxies, even up to an order of magnitude, can still be due to the different gas excitation conditions imposed by the more likely presence of a central starburst in type 2 Seyferts.

Two of the most intriguing results of our study, whose significance goes beyond the study of Seyfert Galaxies are the following:

a) The existence of a cold molecular gas phase residing at a large galactocentric radius in galaxies. This seems to be the case irrespective of the type (AGN and/or starburst) and the intensity of nuclear activity.

b) The possibility that there exist physical states of the molecular gas for which the standard way of finding molecular gas mass from the $^{12}$CO J=1–0 luminosity and a standard conversion factor may not be adequate. This could be the case for either very cold and dense gas residing at large galactocentric radii or warm gas whose $^{12}$CO J=1–0 emission is dominated by a non-virialized gas phase.

Regarding the presence of very cold molecular gas we plan to use the new Sub-mm Common User Bolometer Array (SCUBA) that is now operating on the JCMT to examine this ISM component by detecting its dust emission. This new camera is ideal for this purpose because of its high sensitivity and rapid-imaging capabilities. This will allow deep imaging of a large sample of IRAS galaxies at 850μm and 450μm in a reasonable time. This sample consists of galaxies with various morphologies and varying degrees of nuclear (AGN and/or starburst) activity. Moreover, besides 100μm and 60μm there are also measurements of $^{12}$CO J=1–0 and HI luminosities (or sensitive upper limits). Hence, this sample is ideal for studying the cold dust content and its relation to the other ISM tracers as a function of galaxy type and degree of nuclear activity.

A complementary approach is to use sensitive observations of rare isotopes like $^{13}$CO, C$^{18}$O together with measurements of the mm/sub-mm continuum of the dust emission to probe the conditions of the gas/dust in regions with various degrees of star forming activity within a single galaxy. It can be easily shown that, for an isotope
like C^{18}O that has small/moderate optical depth, ratios like I_{sub-mm}/I_{J+1,J}(C^{18}O) are very sensitive to gas/dust temperature. Hence a combination of sub-mm continuum and CO isotope spectral line data may provide us with a valuable temperature probe for the ISM. The emission from such rare isotopes is usually weak, and in this sense the commissioning of the next generation, sensitive sub-mm spectral line receivers like B3 on JCMT is very timely. This approach is more easily implemented in the case of the strong CO emission associated with the warm gas found in starburst nuclei rather than the cold gas at larger galactocentric radius.

Finally the characteristics of the non-virialized gas phase dominating the observed $^{12}$CO emission must be investigated further. An attractive “laboratory” for such studies are the extreme environments found in powerful IRAS-luminous galaxies like Mrk 231 or NGC 7469. For these systems the use of the standard galactic conversion factor yields very large molecular gas masses, comparable or larger than the dynamical masses. This points to an obvious failure of the standard method to properly account for the molecular gas mass present. While this can be the result of a specific geometry (e.g., Mrk 231, Bryant & Scoville 1996) of the molecular gas distribution, our studies of the more modest starburst galaxy NGC 1068 suggest that the contribution of a non-virialized gas phase can be a very important factor.

Observations of the mm/sub-mm emission from the dust in such galaxies can provide an independent estimate of the gas mass present in their nuclear regions. Similarly a multi-line study of $^{12}$CO and its isotopes $^{13}$CO, C^{18}O can provide us with information on the state of the molecular gas in these extreme environments and possibly with more reliable molecular gas mass estimates that can then be compared to the dynamical masses.

However, a meaningful study of such systems is still hampered by the fact that the resolution of the available mm/sub-mm single-dish telescopes is not adequate to sample only the inner 0.5-1 kpc of the most powerful IR-luminous galaxies, where the starburst and the warm gas resides. Nevertheless interferometers can be employed to observe the J=1-0, 2-1 transitions of $^{12}$CO, $^{13}$CO and C^{18}O at a high enough resolution. Moreover sub-mm observations at $\sim 350-450\mu$m with SCUBA correspond
to a resolution of $\sim 6'' - 7''$, which starts resolving the inner 0.5-1 kpc in a few powerful IR-luminous Seyfert galaxies with NGC 7469 being a prominent one.

Our study and the aforementioned outline of our future goals makes apparent the fact that the increased sensitivity of mm/sub-mm single-dish telescopes and interferometers and the commissioning of a new generation of sensitive continuum sub-mm cameras like SCUBA will allow the probing of the ISM medium at a high sensitivity and resolution. This opens up a new era of discovery where routine observations of rare CO isotopes and cold dust will be possible for a large number of galaxies, not just the brightest and/or the nearby ones. This will allow a test of the various models for the spatial and thermodynamic structure of the ISM, under a variety of conditions, and with larger statistical significance than it was previously possible.
Appendix A

Error estimates in millimeter spectroscopy

The measurement of line intensity in mm spectroscopic observations is effectively the measurement of the quantity

\[ T = (V - V_b) T_{\text{sys}} \]  \hspace{1cm} (A.1)

where \( T \) is the line intensity expressed as temperature (e.g. \( T_{MB} \)), \( V \) is the raw spectrum and \( V_b \) is the subtracted baseline level. \( T_{\text{sys}} \) is the effective system temperature, used to calibrate the raw spectrum to the appropriate temperature scale.

Assuming that the errors of these quantities are uncorrelated we can express the error associated with a measurement of \( T \) as follows:

\[ \frac{\delta T}{T} = \left[ \left( \frac{\delta V}{T_{\text{sys}}} \right)^2 + \left( \frac{\delta V_b}{T_{\text{sys}}} \right)^2 + \left( \frac{\delta T_{\text{sys}}}{T_{\text{sys}}} \right)^2 \right]^{1/2} \]  \hspace{1cm} (A.2)

Two factors contribute to the errors \( \delta V \) and \( \delta V_b \). The one is purely thermal noise and the other comes from all other sources of error like pointing and focusing errors. Assuming again that these two factors are uncorrelated we can write

\[ (\delta V)^2 + (\delta V_b)^2 = (\delta V(\text{th}))^2 + (\delta V_b(\text{th}))^2 + (\delta V_s)^2 \]  \hspace{1cm} (A.3)
where $\delta V(\text{th})$, $\delta V_b(\text{th})$ are the thermal noise errors and $\delta V_*$ is the non-thermal contribution.

The third factor in Equation A.2 has also two different contributing components. The first one is due to a $T_{\text{sys}}$ drift that itself could be due to a variety of factors like variations in the physical temperature of the calibrating loads, rapidly varying atmospheric conditions. For all practical purposes we can consider this drift stochastic in nature. The other contributing factor is a systematic one and it has to do with the fact that the telescope efficiency factors that go into the estimate of $T_{\text{sys}}$ have their own rms errors that will cause a systematic offset in the estimated line intensities. Hence we can write

$$\left(\frac{\delta T_{\text{sys}}}{T_{\text{sys}}}\right)^2 = \left(\frac{\delta T_{\text{sys}}}{T_{\text{sys}}}\right)_{\text{scale-drift}}^2 + \left(\frac{\delta T_{\text{sys}}}{T_{\text{sys}}}\right)_{\text{syst}}^2$$

where we have assumed that the two contributions are uncorrelated. If we express the residual rms (rrms) contribution of all non-thermal, stochastic errors as

$$\left(\frac{\delta T}{T}\right)_{\text{rrms}} = \left[\left(\frac{\delta T_\text{th}}{T}\right)^2 + \left(\frac{\delta T_{b(\text{th})}}{T}\right)^2 + \left(\frac{\delta T}{T}\right)_{\text{rrms}}^2 + \left(\frac{\delta T_{\text{sys}}}{T_{\text{sys}}}\right)_{\text{syst}}^2\right]^{1/2}$$

we can then write the final expression for the total error in the line intensity as follows:

$$\frac{\delta T}{T} = \left[\left(\frac{\delta T(\text{th})}{T}\right)^2 + \left(\frac{\delta T_{b(\text{th})}}{T}\right)^2 + \left(\frac{\delta T}{T}\right)_{\text{rrms}}^2 + \left(\frac{\delta T_{\text{sys}}}{T_{\text{sys}}}\right)_{\text{syst}}^2\right]^{1/2}$$

The systematic error doesn’t contribute to the total error in the case of $^{12}\text{CO}/^{13}\text{CO}$ or $^{18}\text{O}/^{13}\text{CO}$ line ratios for the same transition provided that the telescope efficiency factors aren’t found to vary in the respective observing runs. This is simply because at the neighboring frequencies that correspond to the same transition of different CO isotopes, the associated telescope efficiency factors are identical and they enter the expression of $T_{\text{sys}}$ multiplicatively. In all other cases we assume the contribution of that factor to be of the order of $\sim 10\%$ for both the NRAO 12m Telescope and the JCMT.
The thermal noise factors are easily estimated from statistical analysis of the spectrum itself from which we deduce the noise per channel $\sigma_{\text{ch}}$. If $T$ is the average over $N_{\text{ch}}$ channels with a baseline set by $N_{\text{bas}}$ channels, then $\delta T(\text{th}) = N_{\text{ch}}^{-1/2} \delta T_{\text{ch}}$ and $\delta T_b(\text{th}) = N_{\text{bas}}^{-1/2} \delta T_{\text{ch}}$. Hence the total thermal rms term can be expressed as

$$
\left( \frac{\delta T}{T} \right)_{\text{ther}} = \frac{\delta T_{\text{ch}}}{T} \left( \frac{N_{\text{bas}} + N_{\text{ch}}}{N_{\text{bas}} N_{\text{ch}}} \right)^{1/2}
$$

(A.7)

In order to estimate the residual rms ($\text{rrms}$) non-thermal noise factor we repeatedly observed many bright standard lines with very high S/N ratios. Then the observed dispersion of the line intensities is dominated by the ($\text{rrms}$) factor in Equation A6.
Aalto, S. 1994, PhD thesis, Chalmers University of Technology
Allen, R. J. 1996 in “New Extragalactic Perspectives in the New South Africa”, eds
D. L. Block & J. M. Greenberg (Kluwer; Dordrecht), 50-60.
444, 157
252, 210
Braine, J., Combes, F., Casoli, F., Dupraz, C., Gerin, M., Klein, U., Wielebinski, R.,
& Brouillet, N. 1993 A&A Suppl. 97, 887
192, L17
Fath, E. A. 1909, Lick Obs. Bull. 5, 71
Goldsmith, P. F., Bergin, E. A., & Lis D. C., 1997, IAU Symposium No. 170, 113
Heckman T. M., Krolik, J., Meurer, G., Calzetti, D., Kinney, A., Koratkar, C.,
Jewell, P. 1990, User’s Manual for the NRAO 12 m Millimeter-Wave Telescope (Tuscon: NRAO)
Richardson, K. J. 1985, PhD thesis, Department of Physics, Queen Mary College, University of London