

CO and [C I] in Nearby Galaxies: Probing Physical and Chemical Conditions

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Abstract. Observations of CO can provide constraints on the density and temperature of the dense star-forming gas in galaxies, while observations of [C I] trace photon-dominated regions and provide information on the amount of atomic carbon in molecular clouds. In this paper, I review CO and [C I] observations of nearby galaxies, with an emphasis on galaxies for which high-resolution observations of multiple transitions and isotopologues are available. I also briefly discuss upper limits on water emission from nearby starburst galaxies and on O₂ emission in the SMC obtained with the Odin satellite.

Keywords. galaxies — millimeter interferometry — molecular abundances

1. Introduction

Observations of gas-phase atoms and molecules in galaxies allow us, in principle, to study astrochemistry in physical environments that are quite different from those found in our own Galaxy, *e.g.*, lower abundances of heavy elements, stronger radiation fields, etc. However, one of the difficulties in observing molecular species in even the nearest galaxies is that the lines are quite weak, which limits us to observing only the most abundant species and only a few lines from each species. In addition, the relatively low spatial resolution that is obtained in observations of galaxies means that our data are probing a mixture of chemical and physical conditions, which makes the interpretation more difficult. Finally, the strongest molecular line, ¹²CO, is generally optically thick and not in local thermal equilibrium across even its lowest rotational transitions, which requires more complicated radiative transfer models for its interpretation. All these factors produce the result that the very nearest galaxies are the easiest to study.

Aside from starburst galaxies (discussed, *e.g.*, in Aalto, this volume), the only galaxy which has been observed in a wide variety of molecular species is the Large Magellanic Cloud (LMC). Johansson *et al.* (1994) present observations of over 20 species and isotopologues towards the N159 complex of H II regions in the LMC. They are able to deduce a number of abundances from this data set as well as place constraints on the rotational temperature of several species. For example, they find a [¹²CO]/[¹³CO] abundance ratio of 50 ± 20 , very similar to that in the Milky Way (Langer & Penzias 1990), while the [¹⁸O]/[¹⁷O] ratio of 2 ± 0.5 is a factor of two below the Galactic value.

Recent observations by Brouillet *et al.* (2005) illustrate the difficulties in observing species other than CO even in normal galaxies that are very nearby. They used the IRAM 30 m telescope to observe several regions in the nearby spiral galaxy M31 in the ground-state rotational transitions of HCN and HCO⁺. Figure 1 in their paper shows their HCN and HCO⁺ detections compared to the ¹²CO *J*=1–0 spectra, which are roughly fifty times stronger than the HCN and HCO⁺ lines in a given region. It is this extreme

weakness of the lines from less abundant species that has limited detailed astrochemical work on nearby galaxies.

2. CO in Nearby Galaxies

There have been a large number of observations of CO emission from nearby galaxies in the last two decades and so I make no attempt to be complete in my discussion here. Good starting points for CO $J=1-0$ data are the FCRAO survey by Young *et al.* (1995) and the BIMA SONG survey by Helfer *et al.* (2003); Dumke *et al.* (2001) discuss extended CO $J=3-2$ mapping of a number of nearby galaxies. In this section, I discuss CO observations of nearby galaxies with high intrinsic spatial resolution and observations of multiple transitions or isotopologues. I start with a somewhat older study of M33 by Wilson, Walker, & Thornley (1997), which gives a good illustration of the types of models and assumptions that are required. I then review some recent results from the Smithsonian Submillimeter Array (SMA) by Iono *et al.* (2006) and Petitpas *et al.* (2006) which illustrate the promise of submillimeter interferometry for this research.

2.1. Giant Molecular Clouds in M33

At a distance of 0.84 Mpc (Freedman, Wilson, & Madore 1991), M33 is close enough that large single dish telescopes can isolate the emission from individual giant molecular clouds in the disk. Wilson, Walker, & Thornley (1997) carried out a study of the $^{12}\text{CO } J=2-1$ and $J=3-2$ and $^{13}\text{CO } J=2-1$ emission from seven molecular clouds in M33 that had been previously identified in interferometric CO $J=1-0$ observations. The data revealed very uniform intensity ratios for $^{12}\text{CO } J=2-1/J=1-0$ and $^{12}\text{CO}/^{13}\text{CO } J=2-1$ emission, but showed significant variations in the $^{12}\text{CO } J=3-2/J=2-1$ intensity ratio. Fitting all the data with large velocity gradient (LVG) models (*e.g.*, Scoville & Solomon 1974) gave typical values of $4 \times 10^3 \text{ H}_2 \text{ cm}^{-3}$ for the molecular hydrogen volume density and 20 K for the kinetic temperature. The analysis presented in Wilson, Walker, & Thornley (1997) illustrates very clearly the effect that the adopted $[^{12}\text{CO}]/[^{13}\text{CO}]$ abundance ratio has on the physical results of the models (Figure 1). The primary effect is to change the derived value for the ^{12}CO column density, $N(^{12}\text{CO})$, in direct proportion to the adopted abundance ratio. Although it can generally be difficult to separate the effects of volume density and temperature in LVG models with only a few rotational transitions (*e.g.*, Petitpas & Wilson 2000), the apparent link between increased kinetic temperature and the presence of a (bright) H II region led Wilson, Walker, & Thornley (1997) to conclude that the variation in the $^{12}\text{CO } J=3-2/J=2-1$ line ratio was primarily due to variations in the kinetic temperature of the gas.

2.2. High-Resolution Observations of More Distant Galaxies

For galaxies beyond the Local Group, the spatial resolution achievable with even large single dish telescopes declines to the point where we can no longer isolate individual molecular clouds or even small groups of clouds, but rather must focus on the properties of the interstellar medium on kiloparsec scales. Such observations can reveal interesting differences between spiral arm and interarm regions (*e.g.*, Walsh *et al.* 2002) as well as the dynamical properties of the molecular disk. However, to focus on the ~ 100 pc scales where we may expect some degree of chemical and physical uniformity requires millimeter and submillimeter interferometry.

NGC 2903 is a barred spiral galaxy at a distance of ~ 6 Mpc that has been mapped in the CO $J=1-0$ line as part of the BIMA SONG survey (Helfer *et al.* 2003). The CO $J=1-0$ observations show bright emission from the central region along with fainter

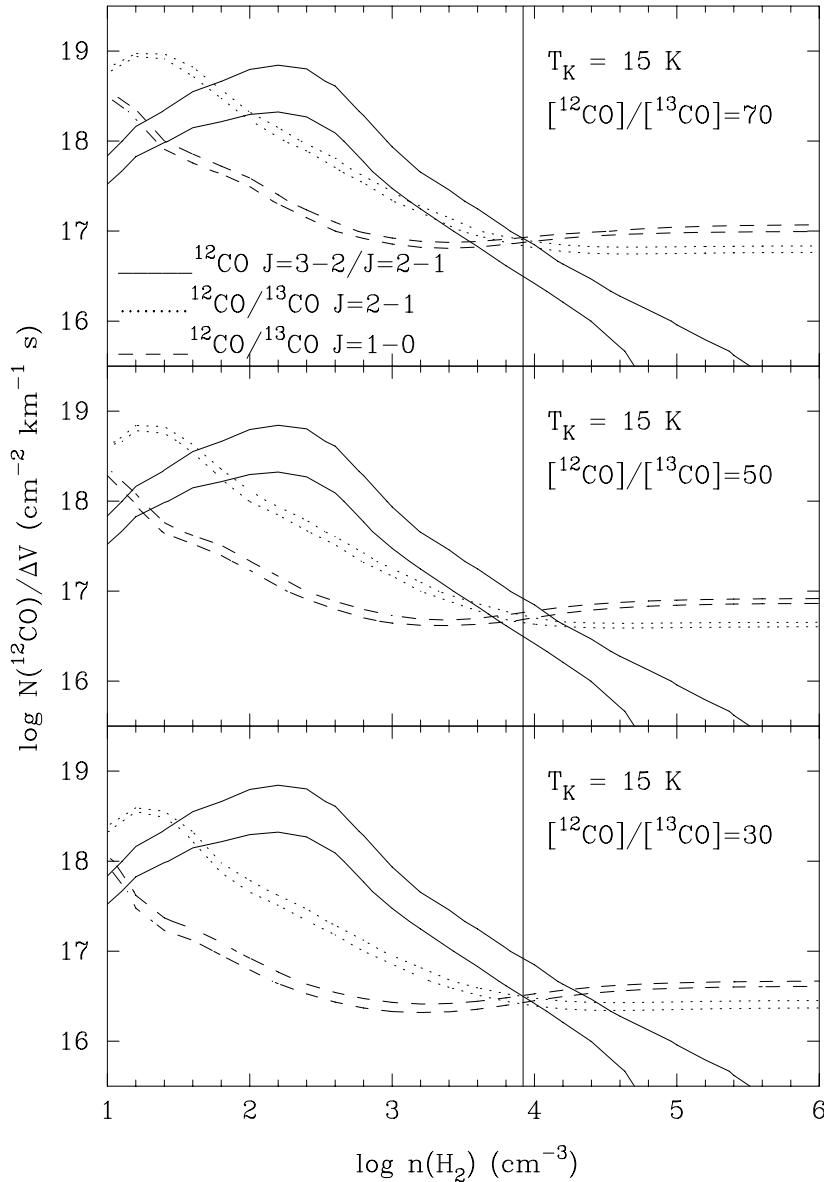


Figure 1. LVG models for molecular clouds in M33 for three different assumed values of the $^{12}\text{CO}/^{13}\text{CO}$ abundance ratio. The lines indicate the $\pm 1\sigma$ values for the observed line ratios of $^{12}\text{CO}/^{13}\text{CO}$ $J=1-0$ (dashed), $^{12}\text{CO}/^{13}\text{CO}$ $J=2-1$ (dotted), and ^{12}CO $J=3-2/J=2-1$ (solid). The vertical solid line indicates the common density solution for all three models. Figure from Wilson, Walker, & Thornley (1997).

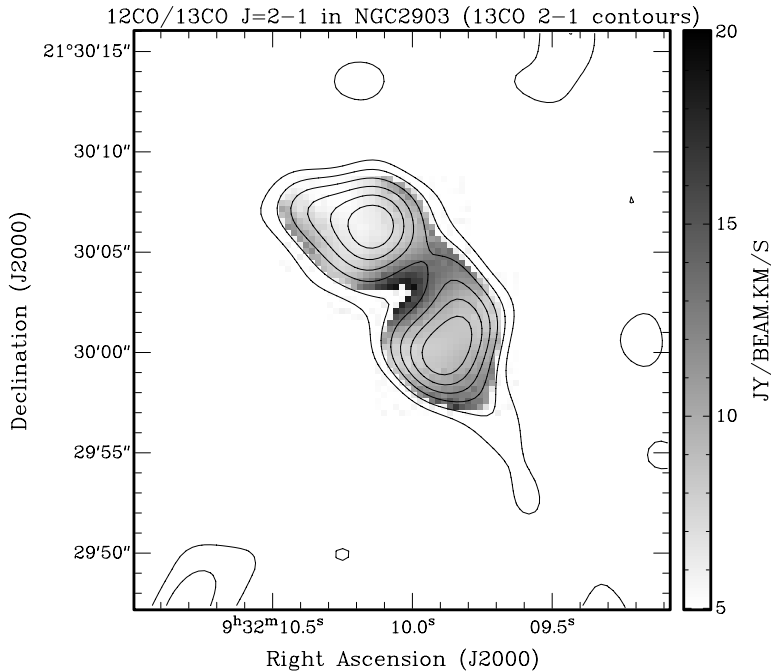


Figure 2. SMA map of the $^{12}\text{CO}/^{13}\text{CO}$ $J=2-1$ line intensity ratio (greyscale) in the central region of the barred spiral galaxy NGC 2903 with integrated intensity contours of the ^{13}CO $J=2-1$ emission overlaid. From Petitpas *et al.* (2006).

emission extending along the inner bar. Petitpas *et al.* (2006) have recently mapped the central region of NGC 2903 in the ^{12}CO and ^{13}CO $J=2-1$ lines with the SMA. The $2.5''$ beam corresponds to a spatial resolution of 70 pc, comparable to the spatial resolution of the M33 study of Wilson, Walker, & Thornley (1997) discussed above. These data reveal a previously undetected double-peaked morphology in the central region; such morphologies are commonly seen in high-resolution CO $J=1-0$ observations of nuclear regions such as those of Kenney *et al.* (1992). What is new in the study of Petitpas *et al.* (2006) is the ability to trace the CO line ratios across the double-peaked morphology (Figure 2). The observations show lower $^{12}\text{CO}/^{13}\text{CO}$ integrated intensity ratios towards the two emission peaks; these lower line ratios most likely trace material with high optical depths and hence high ^{12}CO column densities. What is particularly interesting is the area with high line ratios located in the valley between the two emission peaks. Higher line ratios can indicate either a lower optical depth or a larger intrinsic $^{12}\text{CO}/^{13}\text{CO}$ abundance ratio. Since the ^{12}CO integrated intensity (not shown) is still strong where the line ratio is high, the low optical depth explanation would have to involve some rather unusual excitation conditions. On the other hand, rapid variations in the $^{12}\text{CO}/^{13}\text{CO}$ abundance ratio on the scale of a few hundred parsecs would also be unusual. It is clear there are interesting processes at work in the nucleus of this rather normal spiral galaxy.

Even more intriguing are recent results from SMA observations of the Antennae (NGC 4038/39) by Iono *et al.* (2006). At a distance of 19 Mpc, the Antennae is the closest example of a merger between two large spiral galaxies. Previous interferometric CO

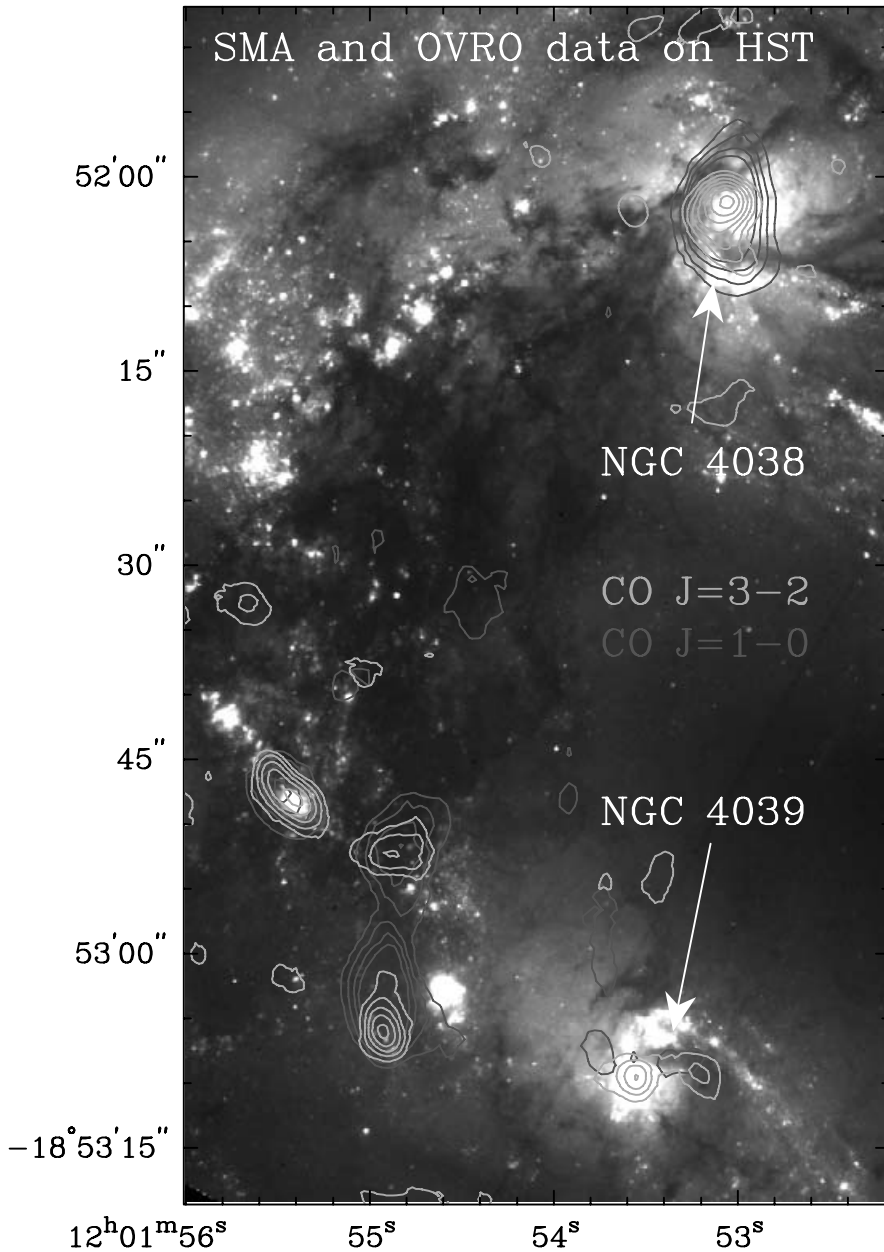


Figure 3. ^{12}CO $J=3-2$ and $J=1-0$ emission (from the SMA and OVRO, respectively) overlaid on the HST image from Whitmore *et al.* (1999) of the Antennae (NGC 4038/39). The two CO data sets have been filtered to have the same resolution and to sample the same range of spatial scales. From Iono *et al.* (2006).

$J=1-0$ observations identified a large number of super-massive molecular complexes with masses approaching $10^9 M_{\odot}$, more than three orders of magnitude larger than the most massive giant molecular cloud in the Milky Way (Wilson *et al.* 2000, 2003). The unusually high masses of the cloud complexes in the Antennae combined with the shocks and high pressures expected in such a large collision have the potential to produce unusual physical and chemical conditions in the molecular gas. Iono *et al.* (2006) have observed

the Antennae in the CO $J=3-2$ line (Figure 3) and have produced a high-quality map of the $^{12}\text{CO } J=3-2/J=1-0$ line ratio by filtering the $J=1-0$ data to have exactly the same resolution and to probe the same range of spatial scales as the $J=3-2$ data. The resulting data cube reveals intriguing variations in this CO line ratio, both spatially *and* in velocity. These variations in line ratio may trace temperature or optical depth variations, while the velocity information helps to separate out physically distinct clouds located along the same line of sight.

3. [C I] in Nearby Galaxies

Gas-phase atomic carbon can be a significant fraction of the total carbon content in galaxies. The amount and distribution of atomic carbon can provide important constraints on the physical and chemical structure of molecular clouds. However, due to the difficulty in observing even the ground-state fine structure line of atomic carbon, there are relatively few published observations of atomic carbon in nearby galaxies. Thus, I have attempted to be complete in my review of published [C I] data in this section.

The first extragalactic observation of the $^3P_1 - ^3P_0$ fine structure line of atomic carbon was made by Stark *et al.* (1997) of the LMC. Wilson (1997) observed four giant molecular clouds in M33 in [C I] emission and found that the [C]/[CO] abundance ratio ranged from 0.03 to 0.16 in the four clouds. The cooling by this single [C I] line accounted for 20–70% of the cooling of the cloud in the lowest three rotational transitions of CO (note that there is an error in the relative cooling rates calculated in Wilson 1997). Most Local Group galaxies have now been observed in the [C I] 492 GHz line [LMC: Kim, Walsh, & Xiao (2004); SMC: Bolatto *et al.* (2000a); M33: Taylor & Wilson (2000); M31: Israel, Tilanus, & Baas (1998); IC10: Bolatto *et al.* (2000b)], albeit in no more than a few positions.

Observations of individual, more distant galaxies in the [C I] line include Arp 220 (Gerin & Phillips 1998), M83 (Petitpas & Wilson 1998; older data are also presented in Israel & Baas 2001), NGC 6946 (Israel & Baas 2001), Maffei 2 and IC 342 (Israel & Baas 2003), and He2-10 and NGC 253 (Bayet *et al.* 2004). In addition, there have been two larger studies of nearby galaxies, one by Gerin & Phillips (2000) using the Caltech Submillimeter Observatory and one by Israel & Baas (2002) using the James Clerk Maxwell Telescope. The data in the Gerin & Phillips (2000) study is more modern than that of Israel & Baas (2002) and Gerin & Phillips also include a comprehensive discussion of published [C I] data from other authors and so I have chosen to focus my discussion on their results.

Gerin & Phillips (2000) find that the [C I]/ $^{12}\text{CO } J=1-0$ intensity ratio is fairly constant, with an average value of 0.2 ± 0.2 , in a wide range of environments (spirals, irregulars, interacting/merging galaxies; see their Figure 3), although there are some variations both within and between galaxies. When compared with the higher rotational transitions of $^{12}\text{CO } (J=2-1, J=3-2, \text{ and } J=4-3)$, the [C I] emission is relatively weaker inside galactic nuclei but stronger in the disks, especially in regions of the disk that are not very active in star formation. They find that atomic carbon makes a significant contribution to the thermal budget, with cooling by C and CO generally of the same order of magnitude (although CO cooling is more important in the starburst galaxies). However, cooling by both C and CO is typically only 5% of the cooling due to ionized carbon and only 2×10^{-5} times the cooling due to the far-infrared continuum emission.

Gerin & Phillips (2000) were able to trace the spatial distribution of the various lines in the edge-on spiral galaxy NGC 891 and found that the [C I] emission traces the 1.3 mm dust continuum emission very well over the inner regions of the disk (see their Figure 5). Since these are the parts of the disk where molecular hydrogen is more abundant than

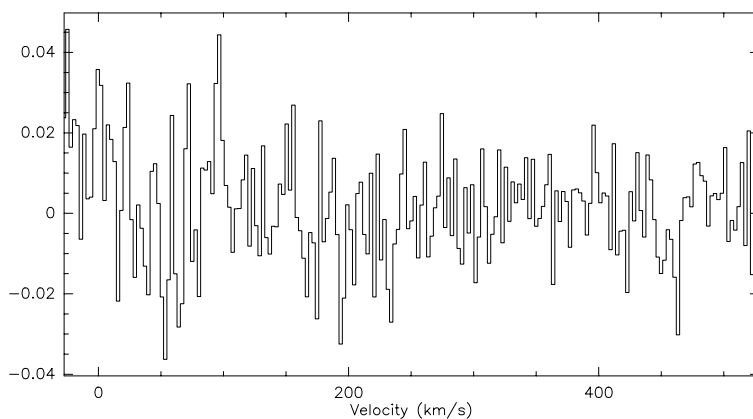


Figure 4. Deep H₂O integration toward the starburst galaxy NGC 253 made with the Odin satellite. The units on the y axis are K (T_A^*). Figure credit: the Odin team.

Table 1. Upper limits to H₂O in galaxies

Galaxy	I(H ₂ O) (K km s ⁻¹)	Predicted I(H ₂ O)
M82	< 1.8	0.4-1.7
NGC 253	< 1.0	0.7-2.8
Cen A	< 2.4	0.4-1.6
IC 342	< 0.5	0.4-1.5
NGC 4258	< 1.3	0.2-0.9

atomic hydrogen, they suggest that [C I] emission may be a good tracer of molecular gas in galaxies, perhaps even more reliable than CO.

4. Recent Results on H₂O and O₂ in Galaxies from Odin

We have used the Odin satellite (Hjalmarson *et al.* 2003) to search for emission in the 557 GHz H₂O line from five nearby galaxies (Table 1). Three of these galaxies are starburst galaxies (NGC 253, M82, IC 342) and two contain active nuclei (Cen A) and water masers (NGC 4258). We restricted our search to nearby galaxies (< 8 Mpc) for which strong emission from the central regions would not be too heavily diluted in the 2' Odin beam. None of the galaxies has been detected in H₂O emission; a representative spectrum is shown in Figure 4.

We estimated 3σ upper limits to the H₂O integrated intensity using the observed CO $J=1-0$ line width; these are given in Table 1. The predicted H₂O intensities in Table 1 were calculated from an estimate of the CO $J=1-0$ intensity in the Odin beam, which was then scaled down by a factor of 12–50 (our estimate of the relative strength of the CO and H₂O emission in the Galactic star-forming region W3; see Wilson *et al.* 2003), to obtain a prediction of the H₂O line intensity. A comparison of the predicted values and the observed upper limits in Table 1 shows that the upper limits obtained with Odin may in some cases place interesting constraints on the structure of the dense interstellar medium in starburst galaxies, but more work is needed to interpret these results.

We have also used Odin to make a sensitive search for O₂ emission in the Small Magellanic Cloud (SMC) using the ground-state 118.75 GHz line (Wilson *et al.* 2005).

The SMC is an interesting galaxy in which to search for O₂ because its abundance of heavy elements is approximately 1/10th that of the Milky Way. Astrochemical models by Frayer & Brown (1997) have suggested that the abundance of O₂ may be enhanced in lower metallicity gas. Our 3 σ upper limit to the O₂ emission corresponds to an upper limit on the O₂/H₂ abundance ratio of $< 1.3 \times 10^{-6}$, a factor of 20 higher than the best O₂ abundance limit obtained for a Galactic source by Pagani *et al.* (2003). [However, it is important to note that O₂ has proved notoriously difficult to detect even in our own Galaxy (Goldsmith *et al.* 2002; Pagani *et al.* 2003). A possible detection of O₂ emission from ρ Oph is discussed by Liseau *et al.*, this volume.] By comparing our abundance limit with a variety of astrochemical models, we find that the low O₂ abundance observed in the SMC is most likely to be produced by the effects of photo-dissociation on molecular cloud structure in gas with a low abundance of heavy elements. Another possibility is freeze-out of molecules onto dust grains, but theoretical models involving this process in gas with a reduced abundance of heavy elements are not yet available.

5. Future Instruments and Prospects

The Atacama Large Millimeter Array (ALMA), now under construction in the Atacama desert of northern Chile, promises to be an incredible instrument for studying nearby galaxies. ALMA will provide much better sensitivity than individual single dish telescopes combined with the ability to achieve routine angular resolutions of 1'' or less. For galaxies within 20 Mpc, the high sensitivity of ALMA will allow us to observe many more molecular tracers (HCN, HCO⁺, and others), which will allow us to begin to do real astrochemistry in galaxies other than the LMC. In these nearby galaxies, new space missions such as Herschel will also make important contributions in the study of atoms and molecules at far-infrared wavelengths which are not visible from the ground. For example, much more sensitive observations of H₂O in galaxies will be possible with the HIFI instrument on Herschel. For more distant galaxies, the low angular resolution of Herschel will limit it to more global studies. However, ALMA will have enough resolution and sensitivity to allow us to study galaxies out to distances of 200 Mpc with the same tracers (CO, [C I]) and spatial resolution that we now use to study galaxies within 10 Mpc. By allowing us both to study more distant galaxies and to study nearby galaxies in greater detail, ALMA promises to revolutionize our understanding of the physical and chemical processes at work in the interstellar medium of galaxies.

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Discussion

PHILLIPS: One of your galaxies looks like M82?

WILSON: Yes, that is NGC2903, which shows a double-peaked structure like M82 in its nucleus. One of the things I didn't have time to discuss here is that, in some galaxies, as you move up the CO rotational ladder that double-peaked structure disappears and you see a single central concentration. So there are clearly some spatial variations in the physical conditions in those galaxies.



Photo: E. Herbst