Physical Conditions and Spatial Structure in the Molecular Interstellar Medium of M33

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Abstract. Early studies of molecular gas in M33 used the CO J=1-0 transition to map out the total gas content in the inner kiloparsec of the galaxy and to study the properties of the giant molecular cloud population. In this review, I discuss recent detailed studies of individual molecular clouds in M33 in higher rotational transitions of CO, 13CO, and the fine structure line of atomic carbon. These data reveal that the temperature and density of the molecular gas is correlated with the presence of nearby massive star formation, with clouds with more intense star formation having higher temperatures and lower densities. This effect is most likely due to post-star formation processing of the molecular gas. A comparison of 13CO observations for M33 and individual molecular clouds in the Milky Way suggests that a significant fraction of the molecular interstellar medium resides in low column density regions and accounts for 30-60% of the CO luminosity. Finally, a detailed map of a single molecular cloud in the giant H II region NGC 604 reveals an offset between the atomic carbon and CO emission, which indicates that the dominant source of atomic carbon in this cloud is likely photodissociation of CO by ultraviolet photons from the massive stars. A complete map of the CO emission in M33 would be extremely helpful to guide further detailed studies.

1 Introduction

Although M33 is substantially smaller than M31, the total Hα luminosities and hence global star formation rates of the two galaxies are quite similar. This higher star formation rate per unit area, along with the presence of very luminous H II regions such as NGC 604 and NGC 595, makes M33 an interesting target for studying its molecular interstellar medium. The first observations of CO emission in M33 (Young and Scoville 1982; Blitz 1985) suggested that the molecular gas content of this galaxy was relatively low. However, a complete map of the inner kiloparsec of M33 revealed significant CO emission (Wilson and Scoville 1989) corresponding to \(3 \times 10^7\) M\(_\odot\) of molecular gas. Interferometric observations (Wilson et al. 1988; Wilson and Scoville 1990, 1992; Viallefond et al. 1992) have revealed a population of giant molecular clouds with sizes, line widths, and masses that are very similar to molecular clouds in the Milky Way. A recent reanalysis of the M33 data along with similar data sets for M31 and the Milky Way by Sheth et al. (these proceedings) uses several different techniques for identifying and analyzing the molecular clouds. The results of that study show that the properties of molecular clouds in these three galaxies are very similar when the clouds are all analyzed in a self-consistent way.

Although there have been major campaigns over the last 10 years to map the total molecular disk of M31 (Dame et al. 1993; Neininger et al. 1998; Loinard et al. 1999; Guélin, these proceedings), we still do not have a complete map of the CO emission in M33. Therefore, instead of discussing the global properties of the molecular interstellar medium in M33, I will focus on recent detailed analyses of specific regions in M33. These studies use observations of the higher rotational transitions of 12CO, the rarer isotopomer 13CO, and the fine structure line of atomic carbon to study the physical conditions and structure of the molecular interstellar medium in M33. In Section 2, I discuss how observations of multiple rotational transitions of 12CO and 13CO can be used to constrain the density and temperature of the molecular gas, and how these properties relate to the local star formation.
environment. In Section 3, I review the evidence for a component of molecular gas at low column densities from observations of $^{13}$CO in M33 and in molecular clouds in the Milky Way. In Section 4, I summarize recent observations of atomic carbon in several molecular clouds in M33 and, in particular, a map of the [CI] emission from a molecular cloud in the giant H II region NGC 604. I conclude with some suggestions for future work on the molecular interstellar medium in M33.

2 Physical Properties of Molecular Clouds and the Link to Star Formation

It seems reasonable to expect that the star formation properties of a molecular cloud may be affected by the physical conditions in the cloud. For example, it is sometimes suggested that the types of stars that form may be affected by the temperature of the cloud (Turner 1984), while the total star formation efficiency of a cloud may be tied to the mass fraction of the cloud in dense cores (i.e. Lada et al. 1991). However, studying the link between star formation and molecular cloud properties is complicated by the fact that star formation can in turn alter the physical conditions in the molecular cloud by heating, compressing, or photodissociating the molecular gas. The key question here is which process is dominant: are differences in the star formation properties among clouds due to the current physical conditions of the clouds, or do those physical conditions instead reflect primarily post-star formation processing of the molecular gas? M33 offers an excellent opportunity to try to disentangle these effects, since we can study individual molecular clouds in a variety of star formation environments all at a common distance.

![Fig. 1. $^{12}$CO J=3-2 (thick line), $^{12}$CO J=2-1 (medium line), and $^{13}$CO J=2-1 (thin line, scaled up by a factor of 3) for three giant molecular clouds in M33 (Wilson et al. 1997).](image)

Measuring the density and temperature of extragalactic molecular clouds is made more difficult by the sizes and internal structure of the clouds themselves. Molecular clouds are clumpy, which means that the typical density of the material producing the CO emission does not equal the volume-averaged
density ($\rho = M/V$). In addition, single molecular clouds are not large enough to fill the beam of even large single radio telescopes, which means that the kinetic temperature of the cloud is not equal to the observed antenna temperature. The solution to these problems is to combine observations of several rotational transitions of $^{12}$CO and $^{13}$CO with radiative transfer models to constrain the density and temperature of the molecular gas. Wilson, Walker, and Thornley (1997) combined observations of three lines of $^{12}$CO and two lines of $^{13}$CO with a large velocity gradient analysis to obtain individual estimates of the density and temperature for seven giant molecular clouds in M33. Figure 1 shows some of the lines observed for three of the clouds; note in particular how the strength of the $^{12}$CO J=3-2 line increases relative to the $^{12}$CO J=2-1 line as we move from a cloud without an optical H II region (MC32), to a cloud with a normal H II region (MC20), to a cloud located very near a giant H II region (NGC 604-2). Although the $^{12}$CO/$^{13}$CO J=1-0 and J=2-1 line ratios are observed to be very uniform throughout the cloud sample, the $^{12}$CO J=3-2/2-1 line ratios increase by a factor of almost two in the cloud near the giant H II region compared to clouds without optically visible star formation.

The density and temperature of the molecular gas derived from the large velocity gradient models also show significant changes that are correlated with the star formation intensity (Table 1). In particular, the molecular gas located near the giant H II region NGC 604 is both hotter and less dense than the molecular gas in more quiescent regions. In addition, the volume filling factor of the dense gas (which is equal to the ratio of the volume-averaged density to the density derived from the radiative transfer model) is highest near the giant HII region and decreases towards more quiescent regions. Are the unusual physical conditions seen in this cloud likely to be the reason why this region has formed a giant H II region, or do the physical conditions instead reflect the local star formation environment? The intense ultraviolet radiation field produced by the massive stars is likely to increase the kinetic temperature of the molecular gas. The expected effect of star formation on density is a little less clear; density could be increased through shocks and increases in the ambient pressure, but might be decreased through photo-dissociation of the molecules and through conversion of the densest regions into young stars. However, given that a continuous range of all physical conditions (temperature, density, and filling factor) is observed as we move from clouds without optical H II regions to clouds with normal H II regions to a cloud in a giant H II region, it seems more likely that the different physical conditions in these clouds are due to post-star formation changes in the molecular gas, rather than the intrinsic conditions of the pre-star formation molecular cloud.

| Clouds                  | $T_k$  | $n(H_2)$             | filling factor |
|-------------------------|--------|----------------------|----------------|
| NGC604-2                | ≥ 100 K| $(1 - 3) \times 10^3$ cm$^{-3}$ | 17-50%         |
| with H II regions       | 15 - 100 K | $(2 - 10) \times 10^3$ cm$^{-3}$ | 2-20%          |
| without H II regions    | 10 - 20 K   | $(5 - 30) \times 10^3$ cm$^{-3}$ | 0.1-4%         |

3 The Structure of the Molecular Interstellar Medium

Comparing observations of molecular emission lines in galaxies like M33 with similar data for molecular clouds in the Milky Way can provide information on the large-scale structure of the molecular interstellar medium. For example, early observations of the $^{13}$CO emission from external galaxies revealed that the $^{12}$CO/$^{13}$CO line ratio is significantly larger in the disks of spiral galaxies than it is in giant molecular clouds in our own Galaxy (Encrenaz et al. 1979), a difference which has persisted as the galaxy sample has grown. Possible explanations for this difference include a different filling factor in the two lines in the large extragalactic beams (Encrenaz et al. 1979), different $^{12}$CO/$^{13}$CO abundance ratios from one galaxy to another (Casoli, Dupraz, and Combes 1992), and a mixture of giant molecular clouds and low column density (or “diffuse”) molecular material in galactic disks (Polk et al. 1988). M33 presents us with a unique opportunity to test these different scenarios, since
we can observe both individual molecular clouds using millimeter interferometers, and larger areas of the disk using single dish telescopes.

Wilson and Walker (1994) detected $^{13}$CO J=1-0 emission towards eight giant molecular clouds in M33 using the NRAO 12 m telescope. The average $^{12}$CO/$^{13}$CO intensity ratio measured in the 55″ beam is $10.0 \pm 0.09$, which is roughly a factor of two larger than the value observed in the Milky Way. This sample shows no significant variation in the line ratio over regions that vary in metallicity by a factor of three, which rules out metallicity as a factor in the different line ratios, at least for M33. They also mapped a single molecular cloud interferometrically in the $^{13}$CO line using the Caltech Millimeter Array. The molecular cloud has the same filling factor in both $^{12}$CO and $^{13}$CO (Figure 2), and thus different filling factors in the different molecules do not seem to be an important factor in this region. The intensity ratio obtained from the interferometer map is $7.5 \pm 2.1$, which is consistent (within the rather large error bars) with the values of 3-6 obtained in the Milky Way. Thus, the high line ratio observed over 200 pc regions of the disk of M33 seems most likely to be produced by a mixture of low and high column density gas within the radio beam. Wilson and Walker (1994) estimate that between 30% and 60% of the $^{12}$CO intensity in these regions originates in gas with a lower average column density. A significant contribution from low column density gas would affect estimates of the total mass of molecular gas in these regions, since using the standard CO-to-H$_2$ conversion factor for this material would produce an overestimate of the total gas mass.

These conclusions are supported by recent studies of giant molecular clouds in the Milky Way. Carpenter, Snell, and Schloerb (1995) mapped a 200x200 pc region of the Gem OB1 molecular complex in both $^{12}$CO and $^{13}$CO with the FCRAO 14 m telescope. They found that the $^{12}$CO/$^{13}$CO intensity ratio is smallest in regions with strong $^{12}$CO emission (2-5), higher in low intensity regions (10-15), and highest in regions where only $^{12}$CO emission is detected (47 $\pm$ 8). Roughly 50% of the $^{12}$CO luminosity originates in regions without detectable $^{13}$CO emission. Calculating the gas mass from the optically thin $^{13}$CO line where it is detected, and the $^{12}$CO line plus an assumed optical depth at other locations, the authors estimate that the 50% of the $^{12}$CO luminosity from low brightness
regions accounts for only 19% of the total mass. Most of the molecular gas in the cloud complex lies in relatively low column density regions ($< 10^{22}$ cm$^{-2}$).

Wilson, Howe, and Balogh (1999) have carried these studies to higher rotational transitions with a 10x20 pc map of the M17 molecular cloud. They also see larger $^{12}$CO/$^{13}$CO line ratios in the J=2-1 and J=3-2 transitions in regions with lower $^{13}$CO peak temperatures, which correspond to regions with lower column densities (Figure 3). The overall trend seen in Figure 3 is primarily due to variations in the gas column density from point to point in M17. The $^{12}$CO/$^{13}$CO line ratios averaged over the whole cloud are 4.5 ± 0.7 for the J=2-1 lines and 3.7 ± 0.9 for the J=3-2 lines. These line ratios are significantly smaller than typical extragalactic ratios of 7-13 and 5-17, respectively, and show that the trend of increasing $^{12}$CO/$^{13}$CO line ratios on larger spatial scales is present for all three of the lowest rotational transitions. Again, the most likely explanation for the higher line ratios in other galaxies is a substantial contribution to the $^{12}$CO emission lines from low column density molecular gas.

4 Atomic Carbon Emission in M33

Atomic and ionized carbon provide important probes into the physical and chemical structure of giant molecular clouds. Because the photodissociation energy of CO and the ionization energy of C are very similar, atomic carbon was originally expected to exist in only a thin layer sandwiched between molecular and ionized regions. However, where [CI] has been searched for over large enough areas, it is generally found to be much more extended than expected (Keene et al. 1985; Plume, Jaffe and Keene 1994; Plume et al. 1999). Since atomic carbon can be produced by photodissociation of CO by ultraviolet radiation, the primary interpretation of this large extent is that the molecular clouds are sufficiently clumpy to allow radiation to penetrate deep into the cloud. However, the large extent of the [CI] emission also raises the question of whether nearby massive star formation is required to produce
atomic carbon, or whether it can be produced by the general interstellar radiation field, perhaps via ultraviolet photons from field OB stars or leaking from H II regions (see also Hoopes and Walterbos, these proceedings). In addition, cosmic rays and chemical processes involving H+ may also be able to produce significant amounts of atomic carbon (Pineau des Forêts, Roueff, and Flower 1992).

Mapping large regions of Galactic molecular clouds in [CI] emission is time consuming even with specialized single-dish telescopes (i.e. Sekimoto et al. 1999) or from space (i.e. Howe et al. 2000, and other papers in the SWAS special issue). Nearby galaxies like M33 offer us the opportunity to measure the total [CI] emission of individual molecular clouds in just a few pointings. Wilson (1997) obtained the first [Cl] detections of four molecular clouds in M33 in single pointings centered on the CO peak for each cloud. Atomic carbon was detected in all four clouds, even in one cloud without an optical H II region. The presence of [CI] emission in this cloud suggests that a nearby region of massive star formation is not required to produced atomic carbon. The [CI] to CO integrated intensity ratio for the four clouds shows significant variation, ranging from 0.04 to 0.18, with the two clouds near optical H II regions showing the largest values.

One unusual result from the Wilson (1997) study is the relatively weak [CI] emission from the molecular cloud NGC 604-2. Since this cloud is located on the edge of the giant H II region NGC 604 and, in addition, has below-solar metallicity, simple arguments suggested that atomic carbon should be especially enhanced in this cloud. Taylor and Wilson (2000) obtained a small [CI] map of this cloud to determine the full extent of the atomic carbon emission. Figure 4 shows the [CI] spectra overlaid on a greyscale image of the CO J=1-0 emission obtained with the Caltech Millimeter Array, while Figure 5 shows the [CI] emission compared to an Hα image. In addition to the [CI] line detected towards the peak of the CO emission, there is an even stronger line located north-west of the CO peak in the direction of the H II region. The offset in the [CI] emission towards the H II region suggests that atomic carbon is created primarily by ultraviolet radiation from the nearby massive stars. However, the presence of [CI] emission towards the center of the cloud indicates a significant ionization fraction in the cloud’s interior. However, [CI] emission is not detected towards the south-east side of the cloud, even though the CO intensity is comparable to that of the north-west position where strong [CI] emission is seen. Overall, the asymmetry in the [CI] emission suggests that the interior ionization is most likely produced by penetration of the clumpy interior of the cloud by ultraviolet radiation from the massive stars, rather than by chemical processes or cosmic rays.

5 Future Work

With an impressive CO survey of the inner disk of M31 now completed (Guélin, these proceedings), the lack of a similar survey for M33 now stands out as an important gap in the high-quality data sets on the interstellar medium that are available for M31 and M33. The large interferometric survey of the M33 disk currently underway should result in a large increase in the number of molecular clouds identified in this galaxy (Engargiola, Plambeck, and Blitz, these proceedings). However, depending on how the sensitivity and filtering imposed by the interferometric observations matches the mass and structural scale of the molecular interstellar medium, this survey may not give us an accurate measure of the total molecular gas content of M33. The only substantial extension to the early single dish work of Wilson and Scoville (1989) is the recent major axis strip map of Corbelli (these proceedings), which reveals substantial CO emission at several locations beyond the inner 1-2 kpc. The new high-resolution H I survey of M33 (Thilker, these proceedings) offers the opportunity to carry out an unbiased search for CO emission associated with H I clouds. Such a survey would likely identify molecular clouds across the entire disk, including clouds in low-metallicity regions and regions with unusually low or high star formation activity, and could be the starting point for future detailed studies of the effect of metallicity and star formation on the molecular interstellar medium. However, even such a targeted survey would not give us a complete measure of the molecular gas content of M33. A complete CO survey of the optical disk of M33 using FCRAO or even larger telescope is urgently needed.

Another interesting area for future studies concerns the low mass end of the cloud mass spectrum. The 13CO observations of M33 discussed in Section 3 provide evidence for molecular gas at relatively low column densities. This low column density material could exist in low mass clouds, in more
extended filamentary structures, or might even be simply the outer regions of the more massive molecular clouds. Deep interferometric observations should be able to detect individual molecular clouds as small as $10^4 M_\odot$, which may be the lower mass limit for gravitationally bound clouds (Heyer, Carpenter, and Snell 2000; Heyer, these proceedings). Identifying a population of low mass molecular clouds would have important implications for understanding massive star formation in M33. For example, Hoopes and Walterbos (these proceedings) have identified a population of “field” O stars, i.e. O stars outside large OB associations, which are responsible for 40% of the ionization of the diffuse interstellar gas. Where are the clouds that could form these field O stars? A likely candidate would be a population of $1 - 5 \times 10^4 M_\odot$ molecular clouds, which would be too faint to have been detected in the existing interferometric surveys.

In the broader picture, M33’s proximity makes it an important testing ground for the various proposed star formation laws (i.e. Kennicutt 1989) and for testing models of molecular cloud formation and destruction. It is interesting to see how clearly the two main spiral arms in M33 stand out in the ISO 170 $\mu$m map (Hippelein, these proceedings); being able to identify clearly arm and interarm regions is important for testing many cloud formation scenarios. The relatively steep metallicity gradient in M33 allows us to study the impact of metallicity on the molecular interstellar medium, from practical items such as the effect on the CO-to-H$_2$ conversion factor to more detailed physical properties such as the distribution of carbon between the molecular, atomic, and ionized phases. An important goal for the next decade is to understand in detail the molecular interstellar medium in M33 and M31, both the properties of the molecular gas itself and its relationship to other phases of the interstellar medium and to star formation. This understanding will provide important background to similar studies of more distant galaxies with a wider range of physical and dynamical properties that will be possible with the Atacama Large Millimeter Array.

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Fig. 4. The [CI] spectra from NGC 604-2 plotted on top of a grayscale image of the CO J=1-0 emission from the Caltech Millimeter Array (Taylor and Wilson 2000). The [CI] beam is 12''. Notice the strong [CI] emission both towards the peak of the CO emission and offset from the CO peak towards the northwest.

Fig. 5. The [CI] spectra from NGC 604-2 plotted on top of an Hα image from the HST archive (Taylor and Wilson 2000). The Hα emission in the northwest corner of the image is part of the giant HII region NGC 604.