MOLECULAR CLOUDS IN THE MILKY WAY

PRESENT AND FUTURE CO SURVEYS

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Surveys aren't the most important thing in astronomy — they're the only thing. — J. Ostriker (with apologies to V. Lombardi)

Abstract. Much of what is known about molecular clouds and their relation to star formation and galactic structure has been obtained from the large scale CO surveys. For several reasons, however, these have been done less systematically and less completely than the early 21 cm surveys; a great deal remains to be done. After a very brief general summary of what has been learned, I will emphasize the work now underway on the outer Galaxy and at high and intermediate latitudes. I will also briefly describe work in progress on M31. It will be argued in conclusion that a complete Galactic CO survey at an angular resolution of $1'$ is quite feasible with a dedicated multiple-feed telescope.

1. Introduction

A large part of what is now known about molecular clouds and their bearing on star formation and galactic structure in a spiral system like ours has been obtained from the large scale CO surveys. Among the most important general findings are:

- Molecular clouds are CO clouds. CO is the most readily observed molecule in all or nearly all molecular clouds and the best general tracer of the largely invisible H_2 and He that constitute the overwhelming bulk of the mass.
- Much of the total interstellar gas resides in molecular clouds.
- Essentially all star formation in a spiral galaxy like ours occurs in molecular clouds and the progeny of young stars (H II regions, infrared

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sources, masers, type II supernovae) are generally found in or near molecular clouds—the large ones especially.

- Molecular clouds are excellent tracers of galactic spiral structure.
- The mass spectrum of molecular clouds is steep. Much of the mass is contained in the largest clouds or cloud complexes, the GMCs, which may exceed $1 \times 10^6 M_\odot$ in total mass and represent the largest localized objects in a galaxy like ours.
- The mass distribution of molecular clouds peaks fairly sharply in the crowded spiral arms 4–6 kpc from the Galactic center—the so-called molecular ring.
- In z, the distribution of molecular clouds is approximately Gaussian, with a full width at half maximum of about 120 pc at the molecular ring and increasing slightly as one proceeds outwards to the solar circle. The thickness of the molecular disk is only about half that of the atomic gas, but (not coincidentally) is almost the same as that of OB stars.
- The GMCs are the source of much of the diffuse Galactic high energy γ-ray emission observed by the SAS-2, COS-B, and Compton observatories.

And if space permitted one could add a number of other general findings heavily dependent on the large scale surveys, some now part of the conventional wisdom regarding molecular clouds and so taken for granted.

All of the major CO surveys are direct outgrowths of the first detection of CO with the 12 m telescope—which given the occasion I will call the 36 foot—and the early molecular observations that were done with that pioneering instrument when it was about the only telescope equipped with adequate spectroscopic equipment in the millimeter-wave band. Struck by the ease with which CO could be observed, even with the rather primitive uncooled Schottky receivers available 25 years ago, and by the wide angular extent of the molecular emission in the vicinity of H II regions like the Orion Nebula and Ori B, we quickly realized that smaller telescopes that could be largely dedicated to CO work were needed. It is with instruments of this kind that much of the survey work has been done.

Rather than survey the surveys—hardly possible in the space available here—let me simply describe some of the CO survey work that remains to be done or is underway. Since a rather complete and uniform inventory of local gas was done by the early 21 cm astronomers in less than a dozen years, it might seem strange that after 25 years our Galaxy and its close neighbors would be incompletely studied in the molecule universally accepted as the best tracer of molecular gas, but that is indeed the case. With the development of ultra-sensitive SIS receivers, approaching the quantum limit in the millimeter band, our early expectation that the essential survey work would require only a few years and several Ph. D dissertations has turned out to be exceedingly naive. Our 1.2 m telescopes in Cambridge and Chile have now turned out over 20 dissertations at Columbia, Harvard, and other universities, and there may be that many yet to come.

Although the entire Galactic plane has now been studied in CO, much of it at fairly high resolution with the Massachusetts and Bell telescopes, one has only to step a short distance off the plane—a few degrees—to find large areas that have been studied only at low resolution. Our whole-Galaxy survey at a resolution of 0.5° (Dame et al. 1987), a composite of a number of smaller scale studies done in the U. S. and Chile with our two telescopes, covered an irregular band 10–20° wide with several extensions to include nearby objects like the Orion and Taurus clouds. Many of the off-plane molecular clouds within this large region remain unstudied at higher resolution, and in the vast regions above and below our survey to the Galactic poles—about 80% of the sky or ~30,000 square degrees—only limited surveys have been undertaken.

Here are some CO surveys underway, planned, or possible that I think are particularly needed and of major interest.

2. A Complete Survey of the Second Quadrant and the Perseus Arm

The Perseus Arm, starting in the upper first quadrant of the Milky Way and crossing the entire second quadrant into the third, is one of the most impressive and easily observed spiral features of our Galaxy, optically visible over much of its length and containing some of the best studied Population I objects (e.g., Cas A, NGC 7538, W3). It is prominent in our 0.5° whole-Galaxy survey, well separated kinematically from the Local Arm over at least 80° in longitude. From the first rather primitive CO study of a large longitude range in this direction (Cohen et al. 1980), it was immediately apparent that molecular clouds are excellent tracers of spiral structure—not at all axially symmetric in their Galactic distribution, as some under-sampled studies toward the inner Galaxy had suggested.

A full survey of the Perseus Arm at a resolution much better than 0.5° is a difficult undertaking, because the arm is at least 4° thick in b and is a good deal fainter in CO generally than the inner arms of the Milky Way.

Two ambitious large scale CO surveys of the outer Galaxy towards the Perseus Arm are underway. Heyer in the present volume is reporting on a survey being done at the University of Massachusetts with their excellent array receiver. The other is being done with the CfA telescope. Starting a year ago with a large amount of data taken by previous observers, Dap Hartmann will complete within one year a fully sampled deep survey from about 75° to 206° in l, covering a strip 4° thick, with several extensions to include prominent clouds. The Massachusetts and CfA surveys taken together should shed light on a variety of interesting questions, including the mass spectrum of molecular clouds, the structure of the Local Arm (toward Perseus bifurcated at several places, possibly as a result of multiple supernova explosions), the molecular arm-interarm contrast, star formation beyond the solar circle, and the properties of the distant molecular clouds beyond the Perseus Arm—and much more.

3. A Complete High Latitude Survey

It is only very recently that anyone has had the persistence to attempt a reasonably complete CO survey covering the tens of thousands of square degrees at high Galactic latitude. There have been extensive studies of the molecular gas associated with the infrared cirrus discovered by IRAS, and well sampled and sensitive studies of selected areas, leading to the discovery of quite extensive molecular clouds well off the Galactic plane (e.g., Heithausen et al. 1993).

A year ago Hartmann and Magnani began an unbiased CO survey with the CfA telescope of the entire high-Galactic-latitude sky ($|b| > 30°$) readily accessible from Cambridge ($\delta > -17.5°$). Observations are being made on a locally Cartesian $1° \times 1°$ grid of nearly 16,000 points to a 3σ sensitivity of 0.3 K, as described in a poster contributed to the present meeting. As of April 1996, over 75% of the planned observations are in hand. One of the main goals of this project is to determine rigorously the local mass density represented by the high latitude molecular clouds for comparison with what has already been determined for the normal in-plane population by Dame et al. (1987).

4. High z Gas in the First Quadrant

Unfortunately, even a complete inventory of the molecular cirrus at high latitudes can tell little about the distribution of molecular clouds far from the Galactic plane. Because the cirrus is almost always quiescent and devoid of star formation, distances are difficult or impossible to obtain. There is little evidence to date that the molecular component of the cirrus is anything but the expected small fraction of normal in-plane molecular clouds that happen to lie above or below the Sun in z. For the time being, this is clearly the simplest and most reasonable hypothesis to adopt.

The distribution with z, however, can readily be determined by observing molecular clouds near the terminal velocity several kiloparsecs away in the first Galactic quadrant, which is what Dame has accomplished with the CfA telescope over the past several years (the same, of course, could be done in the fourth quadrant from the southern hemisphere, but to my

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knowledge no one is attempting that). Some of Dame's recent findings are briefly described elsewhere in this volume. His investigation began with an attempt to see whether there was a molecular counterpart to the thick 21 cm disk observed by Heiles (1984) and Lockman (1984) or to the very high-z CO emission claimed by Garcia-Burillo et al. (1992) in the edge-on spiral NGC 891. If, as widely believed, supernovae and stellar winds are responsible for ejecting atomic gas to high z, one might argue that this mechanism would readily dissociate the comparatively fragile molecular gas and no thick molecular disk would be expected. On the other hand, there is a good deal of information to indicate that the disruption of giant molecular clouds by star formation is a ragged, incomplete process and that substantial molecular fragments are sometimes ejected intact, some at a velocity sufficient (i.e., >15 km s^{-1}) to carry them well above the Galactic plane (e.g., Nyman et al. 1987). We decided that it was best to keep an open mind and simply to look for high-z CO.

Briefly, what has been found consistently between Galactic longitudes 23° and 51° are thick wings to the normal distribution of molecular clouds, reminiscent of the Heiles-Lockman thick 21 cm disk, but, as one might suspect, on a reduced scale (Dame & Thaddeus 1994, 1995). This thick molecular disk is also, to within the observational uncertainties, approximately Gaussian in shape, with a thickness that is typically 2–3 times that of the normal in-plane disk. The total molecular mass locked up in this component is far from trivial: about 50×10^6 "$M_\odot$ within the solar circle (under certain assumptions, the most questionable being that the in-plane mass calibration is applicable). There is also distinct structure in the thick-disk gas, but there is not yet enough data to determine the mass spectrum of the putative "clouds" (if that is the right term). The questions raised by this discovery are intriguing: Is the thick-disk component of molecular gas really ejected from nearer the plane, or is it somehow made *in situ*? If ejected, just how—by what specific mechanism that avoids dissociation? And what are the dynamical effects of this component on the halo and disk of the Galaxy?

5. The Outer Galaxy

In the distant second quadrant, Digel and collaborators have shown, from limited CO surveys toward slight ripples observed in the distribution of H I, that there are molecular clouds at or beyond the claimed edge of the optical disk at 18 kpc (Digel et al. 1994). Star formation seems to be associated with at least one of these—paradoxically, the most kinematically distant at 28 kpc (de Geus et al. 1993). There may be at least 100 of these objects north and south, so a more systematic survey than has been done so far is very much in order. Given the sensitivity required, and the flare and warp in the Galactic disk far from the center, that is not an easy task. An array receiver of the kind discussed in §8 below would be of great help.

6. M31

As the nearest external spiral, M31 ought to be one of the best places to study the relationship of molecular clouds to spiral arms, but it has been difficult to come to grips with this system because it is so large in angular size and is on average faint in CO relative to the Milky Way (by a factor of about five). There have been a number of studies of particular clouds and small segments of arms with the big millimeter-wave telescopes (including the 36 foot: e.g., Combes et al. 1977, Blitz 1985) and several large-area studies with the Bell 7 m telescope (Stark et al. 1981; Ryden & Stark 1986; Casoli et al. 1987; see Hodge 1992 for a review), but the only complete CO survey is one done several years ago with our 1.2 m telescope in Cambridge (Koper et al. 1991; Dame et al. 1993).

A deep high resolution CO survey of M31 is now underway, however, with the University of Massachusetts 15 m telescope and its 15 element QUARRY array receiver as part of the doctoral dissertation of Laurent Loinard at the University of Grenoble. As of April 1996, much of the southwest side of the galaxy has been uniformly surveyed at a linear resolution of 150 pc and the results are of considerable interest. Baade's spiral arm S4 near the peak of the M31 molecular ring is delineated with great clarity over at least 10 kpc. Over much of that length, the CO arm-interarm contrast is large: at least 10:1. The highest contrast observed anywhere is only two and one half times larger (in the Milky Way between the Local and Perseus Arms, Digel et al. 1996). Loinard has shown that the GMCs along S4 are about as large and as luminous in CO as those along the Carina Arm of the Milky Way at about the same distance from the Galactic center and that they are spaced along S4 at about the same interval as those along Carina—roughly every 600 pc (Loinard et al. 1996). M31 is apparently a weak molecular galaxy relative to the Milky Way only because its molecular ring is large and there is little CO emission 4-6 kpc from the center where the spiral arms comprising our molecular ring are especially intense. Beyond the radius of the solar circle, the structure of the two galaxies appears to be remarkably similar in molecular clouds.

7. The $J = 2$–1 Line

Professor Hasegawa and his group at the University of Tokyo have constructed a 60 cm telescope to survey the 2–1 CO line, the aperture chosen to match the $8.7'$ beam of our northern and southern 1.2 m telescopes at the

1-0 line. After extensive survey work in Japan (e.g., of the Orion molecular clouds: Sakamoto et al. 1994; the first quadrant Galactic plane: Sakamoto et al. 1995), a copy of this instrument has recently been transported to Chile to study the molecular clouds in the third and fourth quadrants. Papers by Hasegawa and Oka in the present volume describe some of their recent results. These telescopes should prove two of the most useful and active survey instruments during the years ahead.

8. A High-Resolution All-Sky CO Survey

The CO surveys, with their precise kinematic information, have proven repeatedly to be indispensable to the analysis of spacecraft continuum surveys, particularly those in the infrared and at high energy. Molecular clouds are the common denominator. They are the source of much of the Galactic high-energy diffuse γ-rays observed by the COS-B and Compton gamma ray observatories, much of the Galactic far-infrared emission observed by IRAS and COBE, and much of the X-ray absorption (more-or-less local) observed by ROSAT. The CO surveys have the great merit of providing the precise kinematic information that all these continuum surveys require to place objects along the line of sight and for a rounded interpretation generally. Even the lowest resolution CO surveys are higher resolution than any of the gamma ray surveys. It is hardly necessary to add that all the CO surveys have been done at a very small fraction of the cost of any one of the spacecraft surveys.

The spacecraft surveys do have the virtue, however, of very large scale uniform coverage of much or all of the sky. It is clear that a similar all-sky CO survey done at moderately high angular resolution ($\sim 1'$) and at fairly high sensitivity would be an astronomical resource of enormous value to a large number of astronomers—a veritable Palomar Survey of the molecular clouds here and in our nearest extragalactic neighbors. Like the Palomar survey, an all-sky CO survey would be useful for many years. Even with the fairly sophisticated new electronics required, its cost effectiveness would be high.

How could this best be done? One strategy might be to build a single portable instrument capable of surveying the northern sky in about 3 years, after which it could be transported to Chile to do the southern sky in the same amount of time. If the CO 1–0 line is the chosen vehicle, the antenna requirement is not particularly daunting—an aperture in the 7–15 m range, costing say \$1–2M, which would probably represent a minor fraction of the cost of the project. Alternately, one might start with the Bell 7 m antenna, an excellent, thoroughly tested system well able to carry the complicated receivers required for the project. This is not a very portable telescope,

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however, and shipping it south and installing it there would be a major undertaking.

The main expense would be in receivers and spectrometers. The survey would require a cryogenic multi-feed receiver like the QUARRY array now operating so effectively at the University of Massachusetts, but with many more beams—probably at least 30—and with a spectrometer array to match, either digital or acousto-optical. It would clearly be a mistake to undertake the labor and expense of an all-sky survey without adequate spectral resolution or spectral range, so the spectrometer requirements are formidable but capable of being met: say 5000 resolution elements per beam, each 0.1 km s^{-1} wide, for a fairly generous spectral range of 500 km s^{-1}.

The total survey could probably be done for less than seven million dollars, or less than 0.1% of the runout cost of the Space Telescope, but still a lot of money for a ground-based project of this kind. It is not clear at all in the present climate how such an amount could be found. Too often the catchwords in the funding process are terms like *biggest*, *unique*, and *dramatic*, rather than *useful*, *cost effective*, or *judicious*. Jerry Ostriker's wise dictum quoted at the beginning of this article has yet to sink in.

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