THE CO 2–1/1–0 RATIO

TETSUO HASEGAWA
Institute of Astronomy, The University of Tokyo,
Osawa 2-21-1, Mitaka, Tokyo 181, Japan

Abstract. A Galactic CO J=2–1 survey compatible with the Columbia CO J=1–0 survey has been conducted with a 60-cm telescope at Nobeyama. Molecular clouds in the solar neighborhood exhibit variations of the J=2–1/ J=1–0 intensity ratio from place to place in a cloud and from one cloud to another. This mainly reflects a variation of the hydrogen density near the *CO photospheres*, where the opacity of the lines reaches ~ 1 at cloud surfaces. The ratio often exceeds unity at molecular cloud-HII region interfaces. The Milky Way survey has shown that the average J=2–1/J=1–0 ratio in volume emissivity increases gradually from 0.6 in the solar neighborhood to 0.75 at 4 kpc from the Galactic center. This trend is due to an increased contribution of the gas with higher J=2–1/J=1–0 ratio (≥ 0.7, *High Ratio Gas*) that concentrates in spiral arms in the inner Galaxy. The amount of *High Ratio Gas* there is too large to be explained as molecular gas under direct influence of HII regions; rather, it may be a manifestation of dense molecular gas that is ready to form massive stars.

1. Introduction — Basic Problems

From millimeter wave spectroscopy, we have learned the amount of molecular gas in the Galaxy, its radial distribution, and its spatial structure, especially its concentration to giant molecular clouds (Scoville & Solomon 1975; Burton et al. 1975; Sanders, Solomon, & Scoville 1984; for a recent review, see, e.g., Dame 1993). A natural next step to take is a study of its physical conditions, i.e., its density, temperature, etc. To understand star formation that varies from place to place, we need a knowledge of gas conditions and their variation on spatial scales ranging from dense molecular cloud cores ($\leq 1pc$) to a galaxy (over 10 kpc).

The physical conditions of gas in selected regions of molecular clouds have been studied (e.g., Goldsmith 1987). On a larger scale, gas conditions in the central kiloparsec regions in galaxies are being investigated (e.g., Braine & Combes 1992; Aalto-Bergman in these proceedings). In the IRAS luminous galaxies, the massive central concentrations of dense molecular gas may be responsible for the extremely intense star formation. However, limited spatial resolution often makes it difficult to convert the observed information to the physics of molecular gas.

Our knowledge of the change of the gas condition on a scale range that links cloud internal structures and galactic structures is poor. To fill this gap, we have conducted a survey of Galactic CO J=2–1 emission at 230 GHz with a dedicated 60-cm radio telescope at Nobeyama (Hayashi et al. 1990; Handa et al. 1993). The survey was designed to be compatible with the Columbia survey of the J=1–0 transition (Cohen, Dame, & Thaddeus 1986; Dame et al. 1987); the telescopes have the same beamsize (HPBW = $9'$), and in most cases we observed on the same grid as the 1–0 observations. These cases enable us to measure the 2–1/1–0 line intensity ratio accurately.

In this paper, with the data taken in the last a few years at hand, we address the following questions:

- What is the CO 2–1/1–0 ratio in various clouds with and without massive star formation?
- What makes the ratio high or low?
- How can we understand its galaxy scale variation in terms of formation of clouds and stars?

2. Lessons from Nearby Molecular Clouds

It is often stated that CO lines are optically thick and are in local thermodynamical equilibrium (LTE). If this is the case, the line brightness of any low-J rotational transition becomes $B_\nu(T_\mathrm{k})$, the Planck function at a gas kinetic temperature T_k. However, this textbook understanding is correct only partially. High resolution maps of molecular clouds reveal many clumps and filaments within them. The CO lines get optically thick at small depths at their surfaces. We call these regions *CO photospheres* where most of the CO line photons reaching us are emitted. The gas density there is not necessarily high enough to excite the levels to the LTE limit.

What do we probe by measuring the CO 2–1/1–0 line intensity ratio? Although intensities of both lines roughly scale with the column density of gas, the J=2–1 emission samples warmer and denser regions compared with the J=1–0 emission. By taking their ratio, we can cancel the strong dependence on the *quantity* of gas to examine its *quality*, i.e., the conditions of the gas near the photosphere.

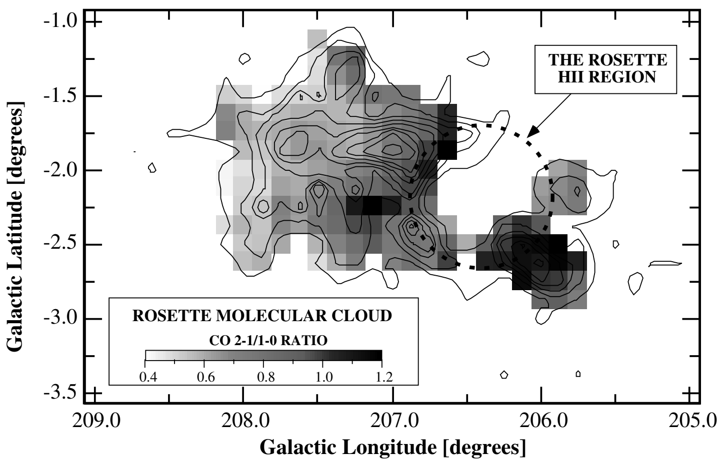

Figure 1. The Rosette Molecular Cloud in CO J=2–1 integrated intensity (*contours*) and the 2–1/1–0 ratio (*grayscale*). The J=1–0 data from Blitz & Thaddeus (1980) and May et al. (1993) were used to derive the 2–1/1–0 ratio. (Morino et al. 1996)

We can get insight into these problems by visiting nearby molecular clouds. Sakamoto et al. (1994) mapped the Orion A and B clouds, the nearest examples of massive ($> 10^5$ $M_\odot$), giant molecular clouds (GMCs) with ongoing massive star formation. The map of the CO 2–1/1–0 intensity ratio formed from the J=1–0 data by Maddalena et al. (1986) shows its global variation over the surface of the cloud (Figs. 2*a, b* in Sakamoto et al. 1994). In the central ridges of the clouds, the ratio is close to, but smaller than, unity (0.9 typically), and becomes smaller (≈ 0.5) in their peripheral regions.

Figure 1 shows another GMC associated with an HII region, the Rosette molecular cloud (Morino et al. 1996). The CO 2–1/1–0 intensity ratio exceeds unity in the molecular shell immediately outside the HII region. The thickness of the gas shell with this very high ratio (> 1.0) is less than 10 pc. Away from this shell, the ratio is 0.7–0.6 in the region of high CO intensity and gets lower (< 0.5) in the cloud boundary to the southeast (to the left in Fig. 1).

As a prototype of less massive ($\sim 10^4$ $M_\odot$) dark clouds with low-mass star formation, the Taurus molecular cloud complex has been observed (Hayashi et al. 1996). The CO 2–1/1–0 ratio derived with the J=1-0 data by Ungerechts & Thaddeus (1987) shows the common systematic variation that the ratio is higher (0.6) in the ridges of the clouds while it is lower (0.4) in their outskirts. It is interesting to note that known protostars and T Tauri stars are located in the regions of higher 2–1/1–0 ratio.

Figure 2 shows the distribution of the 2–1/1–0 intensity ratio in the

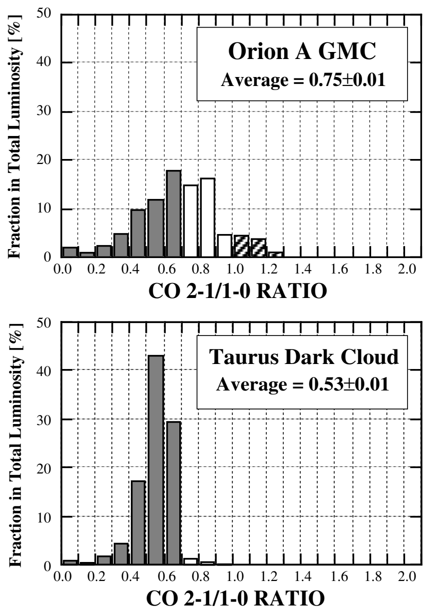

Figure 2. The distribution of the CO 2–1/1–0 ratio in the Orion A giant molecular cloud (*upper*) and the Taurus dark cloud (*lower*). Spatial resolution is 1.2 pc in both cases. Gas with *Low Ratio*, *High Ratio*, and *Very High Ratio* explained in the text are shown shaded, open, and hatched, respectively. CO 2–1/1–0 luminosity ratios of the entire clouds are shown as average ratios; the quoted errors do not include common antenna calibration errors (~ 10 %).

clouds in Orion and Taurus. As the CO luminosity scales with the mass of molecular gas to first order, the Figure shows the mass fraction of molecular gas at certain conditions indicated by the CO 2–1/1–0 ratio. Differences between the two clouds are clear: In the Taurus dark cloud, most emission comes from the gas with a ratio smaller than 0.7. We call it *Low Ratio Gas*. In the Orion A GMC, on the other hand, a significant fraction of the luminosity comes from the gas with the ratio 0.7–1.0 (*High Ratio Gas*) and that with the ratio larger than 1.0 (*Very High Ratio Gas*). The 2–1/1–0 CO luminosity ratios in these clouds are differ accordingly; 0.53 average for Taurus and 0.75 for Orion.

What do these observations mean? A variation in the temperature of LTE gas cannot explain *Low Ratio Gas* unless the gas temperature gets significantly below 10 K. Sakamoto et al. (1994) modeled the variation of the 2–1/1–0 intensity ratio as due mainly to a variation of density at the CO photospheres of clumps that compose the clouds. The photon trapping effect places the CO J=1–0 and J=2–1 photospheres near each other (especially at low densities and temperatures), and this justifies our limited use of one-zone large velocity gradient (LVG) model calculations in excitation analyses of the CO lines there. In this scheme, *Low Ratio Gas* is in the form of clumps with extended envelopes, whose CO photospheres occur at low density. On the contrary, *High Ratio Gas* is in tightly confined clumps with a steep density gradient, which have CO photospheres at higher density.

The above model cannot explain *Very High Ratio Gas* often accompanied by relatively bright ^{13}CO emission. This may reflect small-scale clumping and/or a steep temperature gradient at their surfaces that are expected in photodissociation regions (Gierens, Stutzki, & Winnewisser 1992).

3. The Milky Way Survey

With the understanding of the CO 2–1/1–0 ratio acquired from nearby molecular clouds described above, we can now analyze the Milky Way survey data to see how the conditions of molecular gas vary with location in the Galaxy.

The CO J=2–1 survey of the first Galactic quadrant was made in three parts and covered up to 40% of the inner galactic disk between 2 kpc and 8 kpc from the Galactic center:

- The pilot survey (Handa et al. 1993): $l = 2° - 88°$ sampling at $\Delta l = 1°$ along the Galactic plane ($b = 0°$)
- Two dimensional survey, Part I (Sakamoto et al. 1995): $l = 20° - 60°$, $|b| \leq 1°$, at $\Delta l = \Delta b = 0.25°$ sampling
- Two dimensional survey, Part II (Sorai et al. 1996): $l = 6° - 20°$, $|b| \leq 1°$, at $\Delta l = \Delta b = 0.25°$ sampling ($\Delta l = \Delta b = 0.125°$ for $|b| \leq 0.25°$)

One of the first questions to answer is whether the average condition of the molecular gas in the Galactic disk varies with Galactocentric radius $R_{\rm G}$. Handa et al. (1993) analyzed the pilot survey data with the assumption of axisymmetry and circular rotation at a constant speed. The result reproduced by filled circles in Figure 3 showed a gradient of the CO 2–1/1–0 ratio with $R_{\rm G}$ for the first time.

Similar analyses of the two dimensional surveys improved the spatial sampling by a large factor and confirmed the variation (open symbols in Fig. 3). In these cases we are limited not by observational errors but by intrinsic fluctuations of molecular gas in the disk; we can see this in the discrepancy at $R_{\rm G} > 7$ kpc, where a small number of clouds in the near side dominate an average at constant $R_{\rm G}$. Nevertheless, we see the trend of the CO 2–1/1–0 ratio increasing gradually from 0.6 ($\pm$0.1) in the solar neighborhood to 0.75 ($\pm$0.05) at $R_{\rm G} = 4$ kpc.

In working with small telescopes, beam dilution is a serious problem. Indeed, if we were to identify molecular clouds from our data, incompleteness posed by our spatial resolution and sampling of a few $\times 10$ pc at $R_{\rm G} \approx 4$

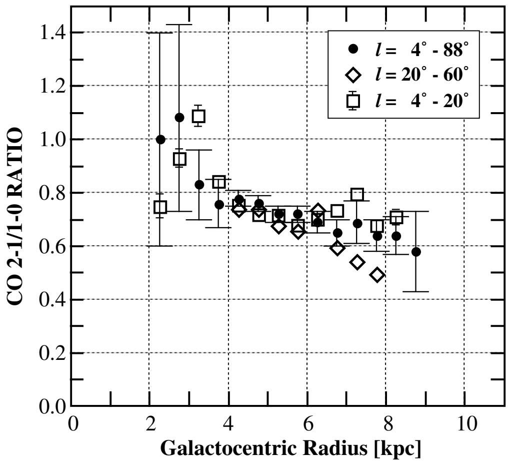

Figure 3. The 2–1/1–0 ratio of the CO volume emissivity as a function of Galactocentric radius, R_{G}. We adopt $R_{\mathrm{G}} = 8.5$ kpc for the Sun. The three marks correspond to the three surveys explained in the text. The J=1–0 data from Cohen, Dame, & Thaddeus (1986) were used to derive the 2–1/1–0 ratio. Indicated errors do not include common antenna calibration errors ($\sim$ 10 %).

kpc would be a large problem. We can avoid this difficulty by measuring the CO line intensities in volume emissivity, the luminosity in unit volume of space in the Galactic disk. The ratios shown in Figure 3 are in volume emissivity, and we are free from these problems.

If we take these 2–1/1–0 ratios superficially and apply the one-zone LVG analysis described in the preceding section, the gradient could be interpreted as an increase of the “mean” photospheric density of molecular clouds in the inner Galaxy. However, molecular gas contributing to the CO luminosity in the Galactic disk is highly heterogeneous.

As the first approximation, we view the gas as composed of *High Ratio Gas* (here we include *Very High Ratio Gas* in it) and *Low Ratio Gas*. The former is found in bright ridges in GMCs, while the latter is in dark clouds and in the peripheries of GMCs. Sakamoto et al. (1996) binned the data with a $\Delta V_{\mathrm{LSR}} = 5$ km s^{-1} resolution, and classified volume elements with detected CO emission in the l-b-V_{LSR} datacube into these two categories. This analysis showed that the higher 2–1/1–0 CO volume emissivity ratio at smaller R_{G} is a reflection of an increased contribution of *High Ratio Gas* that is concentrated in spiral arms of the inner Galaxy.

It is interesting to ask whether the gradient in the CO 2–1/1–0 ratio continues into the Galactic center region. The observations show that, although abundant *Very High Ratio Gas* is found in the midplane, a large amount of *Low Ratio Gas* off the plane counteracts to make the total 2–

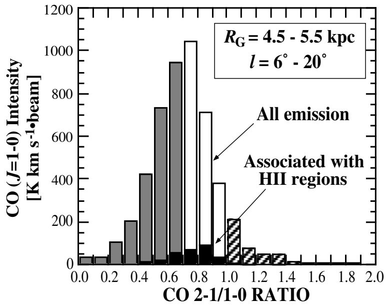

Figure 4. The distribution of the CO 2–1/1–0 ratio in the gas located in the Galactic disk at $R_{\rm G} = 4.5 - 5.5$ kpc and $l = 6° - 20°$. Filled bars show the CO J=1–0 emission coincident in position (within ~ 10 pc) and velocity (within ± 7.5 km s^{-1}) with radio HII regions catalogued by Lockman (1989). (Sorai et al. 1996)

1/1–0 CO luminosity ratio as low as 0.65 for all emission within $|l| \leq 2.5°$, $|b| \leq 1.0°$, and $|V_{\rm LSR}| \leq 150$ km s^{-1} (Oka et al. 1996a, b).

A survey of the outer Galaxy is in progress. In the Perseus arm at $l = 130° - 151°$, the volume emissivity of *Low Ratio Gas* is extremely low (Sato et al. in these proceedings). This may be related to the fact that the H_2/HI abundance ratio turns over at this $R_{\rm G}$.

4. Massive Star Formation and High Ratio Gas

In the solar neighborhood, *High Ratio Gas* has been found only in GMCs so far. It may show surfaces of tightly bound clumps in bright ridges of molecular clouds, where we see many young stars and protostars of intermediate mass. In the Galactic disk, we found that *High Ratio Gas* concentrated along spiral arms. Because massive star formation highlights spiral arms, they may have a causal relationship. Is *High Ratio Gas* a cause or an effect of massive star formation?

As we have seen in Orion and Rosette GMCs, massive star formation results in *Very High Ratio Gas* around HII regions. However, it is limited to < 10 pc from the molecular cloud-HII region interface, and most of the *High Ratio Gas* lies beyond this range of direct effect. It appears that *High Ratio Gas* is *not* a direct effect of OB star formation in GMCs but is related to the massive star formation expected in them. A comparison between the CO 2–1/1–0 ratio and masses of dense cores in various types of clouds would be interesting, because a theory predicts a close relationship between the core mass and the mass of a star that forms in it (Nakano, Hasegawa, & Norman 1995).

For the molecular gas in the Galactic disk we can test the one-to-one correspondence between *High Ratio Gas* and HII regions observed in radio wavelengths in the l-b-$V_{\rm LSR}$ datacube. In general, HII regions are located in or near *High Ratio Gas*, but there is much more *High Ratio Gas* without coincident HII regions (Sakamoto et al. 1996; Sorai et al. 1996). Figure 4 shows this quantitatively for the gas located near the peak of the molecular ring in the Galactic disk. The CO emission coincident with HII regions in position and velocity are indicated by solid bars (we double-count the near- and far-side emission). Although molecular gas directly associated with HII regions exhibits systematically higher CO 2–1/1–0 ratio, it has only a minor ($\sim$ 10 %) fraction in the total CO luminosity from *High Ratio Gas*; most of the *High Ratio Gas* resides outside the range of direct effect of O stars.

The above argument leads us to a working hypothesis that GMCs containing *High Ratio Gas* are formed by some mechanism(s) related to the spiral arms, and they provide sites of massive star formation; *High Ratio Gas* may be a manifestation of dense molecular gas that is ready for massive star formation.

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