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DETECTION OF CLUMP AND INTERCLUMP GAS IN THE ROSETTE MOLECULAR CLOUD COMPLEX

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ABSTRACT

High-resolution, high-sensitivity CO and ^{13}CO observations have been made of the Rosette Molecular Cloud Complex at one beamwidth resolution. Clumpiness of the ^{13}CO is seen everywhere in the complex. The clumps are shown to be easily identified entities with densities ~ 10 times the volume-averaged density of the entire complex. The clumps are shown to be embedded in pervasive *molecular* "interclump" gas of low average volume density ($\langle n \rangle \approx 2$ cm^{-3}) which has not previously been observed. The velocity dispersion of the interclump gas is about 3 times greater than that of the clumps, implying that the gas is not gravitationally bound to the complex. It is shown that no special support of the complex as a whole needs to be postulated to prevent catastrophic collapse.

Subject headings: interstellar: matter — interstellar: molecules — stars: formation

I. INTRODUCTION

Observations of star-forming molecular clouds have shown them to be very inhomogeneous, but little quantitative information exists on the detailed density structure of the clouds. In order to provide hard data on the clumpiness of giant molecular clouds (GMCs), we have undertaken a high-resolution, high-sensitivity survey of CO and ^{13}CO over a large fraction of the Rosette Molecular Cloud (RMC). In this *Letter* we report the discovery of molecular "interclump" gas of low average volume density. This gas appears to be a small fraction of the mass of the molecular cloud complex, and its existence leads us to postulate a "pea-soup" model for giant molecular clouds: a swarm of relatively high-density clumps embedded in a more tenuous pervasive substrate of molecular gas. Support for the cloud as a whole comes from the random motion of the clumps, which are themselves probably supported by magnetic fields and thermal pressure. The interclump gas has a large velocity dispersion and appears to be escaping from the molecular cloud complex.

II. OBSERVATIONS

The observations were carried out at various times from 1982 April to 1985 April using the 7 m telescope at AT & T Bell Laboratories in Holmdel, N.J. The observations were made using an SIS mixer receiver which had SSB mixer temperatures in the range 90–170 K. Typical total system temperatures referred outside the atmosphere were 200 K for ^{13}CO and 650 K for CO. Observations were obtained by both frequency switching and by position switching. The emission-free references for position switching were $l = 207\overset{\circ}{.}515$, $b = -0\overset{\circ}{.}323$ and $l = 207\overset{\circ}{.}515$, $b = 3\overset{\circ}{.}323$. Observations were taken in two modes: survey and low-noise. In the survey mode, observations were generally short (30 s for ^{13}CO, 10 s for CO) so that large areas could be surveyed. In ^{13}CO, 3456 spectra at full beamwidth sampling were obtained over a large fraction (about half) of the cloud mapped by Blitz and Thaddeus (1980). The typical rms noise in a ^{13}CO spectrum is 0.2 K in unsmoothed 0.68 km s^{-1} wide filters. For ^{12}CO, we obtained 4850 spectra with a typical rms noise of 0.8 K. The telescope beam (FWHM) is $1\overset{'}{.}7$ at CO and $1\overset{'}{.}8$ at ^{13}CO; data were sampled every $1\overset{'}{.}5$ which corresponds to 0.7 pc at the 1600 pc distance of the Rosette.

The low-noise mode was used to bring out broad weak features in the data. Integrations in this mode were made at six widely scattered positions; for both CO and ^{13}CO these lasted about 30 minutes, producing typical rms noise of 45 mK and 20 mK, respectively. In the low-noise mode, spectra were taken by position switching only, to ensure that the baselines would be flat.

III. RESULTS

The composite average spectra for all of the CO and ^{13}CO data are shown in Figure 1. Note the broad non-Gaussian wings in the CO spectrum seen at $V_{LSR} = 4$–8 km s^{-1} and $V_{LSR} = 18$–24 km s^{-1}. It is this component that we identify with the "interclump" gas below.

Assuming that the peak CO line temperature in a given direction is equal to the excitation temperature, nearly all of the ^{13}CO has an optical depth considerably less than unity. The line parameters for ^{13}CO are therefore a reflection of the kinematics of the dense gas we associate with the clumps. The velocity centroid of the composite ^{13}CO spectrum is 13.10 ± 0.02 km s^{-1} and the one-dimensional rms velocity dispersion is 2.28 ± 0.03 km s^{-1}. Because we have not mapped the RMC as completely as Blitz and Thaddeus (1980), the small difference between our velocity centroid and theirs (14.3

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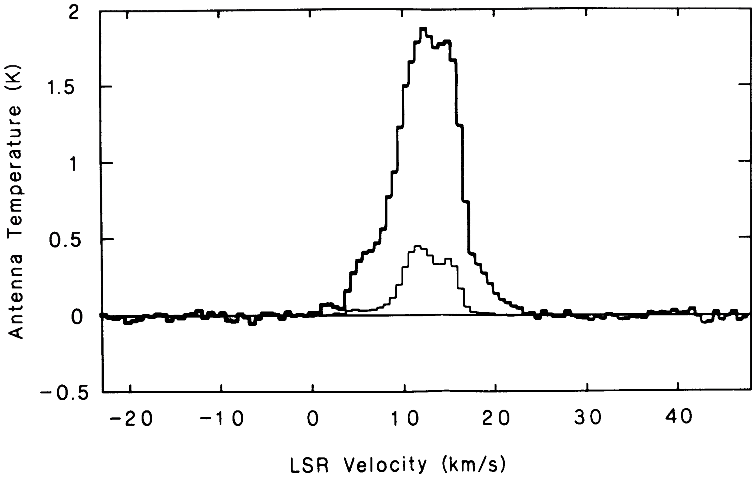

FIG. 1.—Composite average spectrum of all CO (*thick line*) and ^{13}CO (*thin line*) observations made of the Rosette Molecular Cloud Complex within the dashed boundary shown in Fig. 2. Note particularly the line wings at velocities less than 8 km s^{-1} and greater than 18 km s^{-1}.

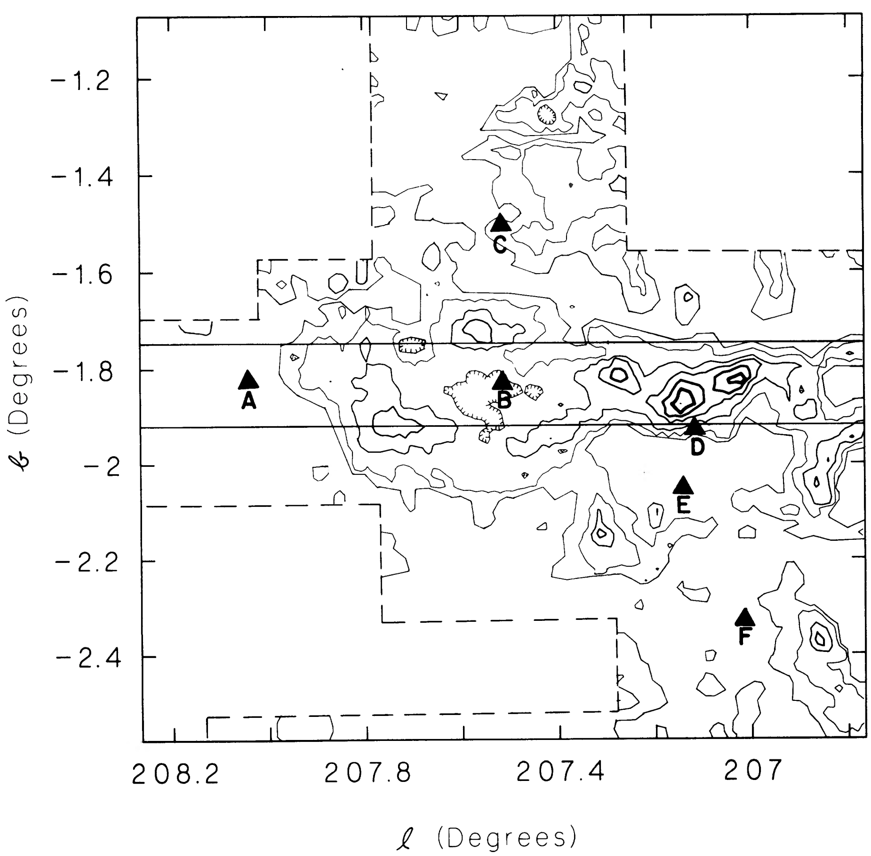

FIG. 2.—Map of $\Sigma T_A^*(^{13}\mathrm{CO})\, dV$ of data taken in the survey mode. The dashed lines indicate the survey boundary. The contour levels are 2, 4, 8, 12, 16, and 20 K km s^{-1}. Low-intensity emission is seen at most positions within the surveyed region; lower contours are omitted for clarity. Because the ^{13}CO is optically thin, the clumpiness represents true density enhancements. The positions marked A–F are the locations of the low-noise spectra discussed in the text. The spectrum at position E is shown in Fig. 4. The horizontal lines are the loci of the longitude velocity plots shown in Fig. 3.

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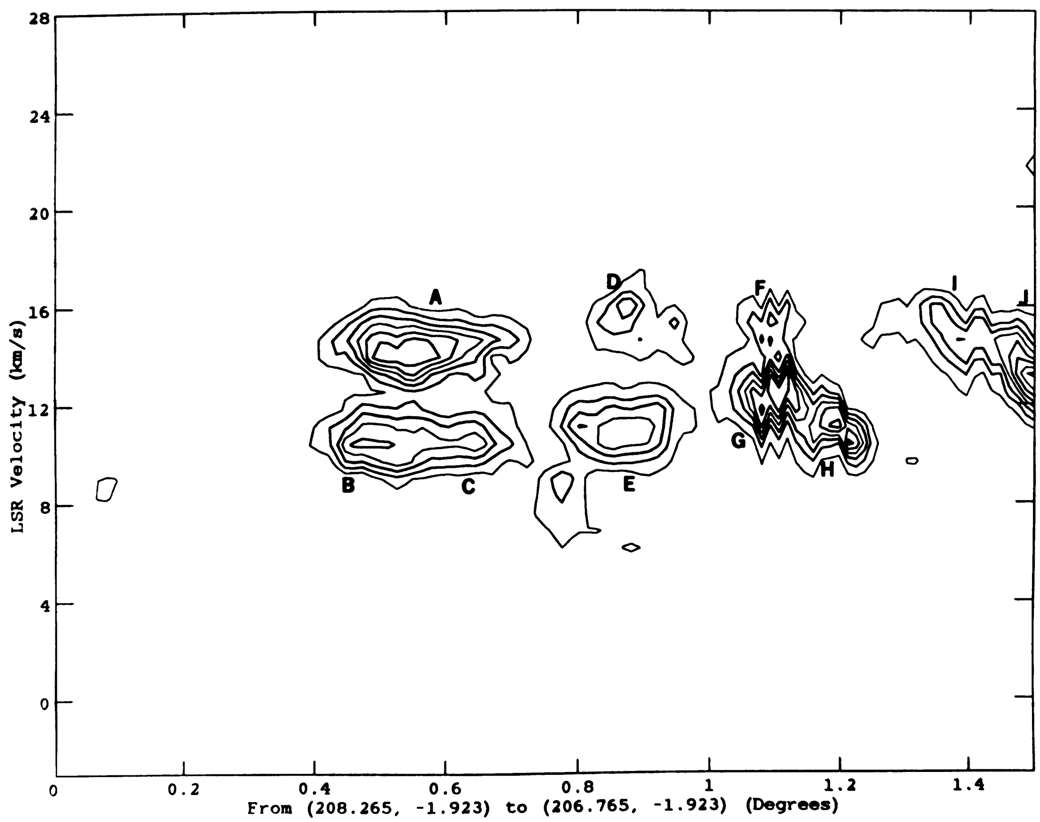

FIG. 3*a*

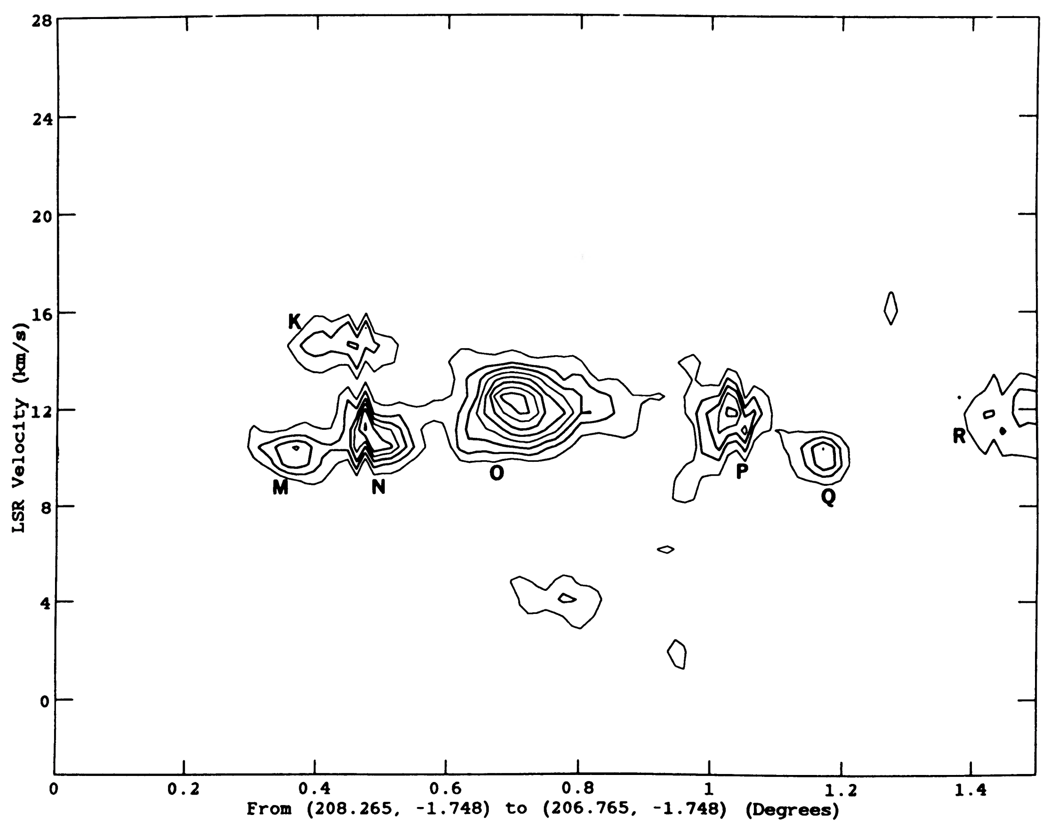

FIG. 3*b*

FIG. 3.—Longitude-velocity plots made at (*a*) $b = -1^\circ.923$ and (*b*) $b = -1^\circ.748$ as shown in Fig. 2. The lowest contour is 0.5 K and the contour interval is 0.5 K. There is much more clumpiness in these plots than is evident in Fig. 2.

km s^{-1}) is not significant. The mean $T_A^*(^{13}CO)$ over the 1100 pc^2 area we observed is 0.45 K and $\Sigma T_A^*(^{13}CO)\, \Delta V = 3.04$ K km s^{-1}.

The map of the ^{13}CO emission integrated over the velocity range 0–20 km s^{-1} is shown in Figure 2. Emission is observed nearly everywhere within the confines of the region sampled (indicated by dashed lines). The clumpy structure of the emission is quite evident in the figure. Because ^{13}CO is mostly optically thin, the apparent clumpiness is the result of true density enhancements in the RMC projected on the *l-b* plane. Examination of the spatial maps made in narrow velocity ranges and of the longitude-velocity and latitude-velocity maps indicate that the clumpy structure is far richer than is apparent in Figure 2; evidently, the emission from many of the clumps is blended together.

This is illustrated in Figures 3*a* and 3*b* which are longitude-velocity plots taken at $b = -1°748$ and $b = -1°923$. These two plots were chosen to show the large number of individual clumps that could be identified in just two of our 60 *l-v* diagrams. The plots also illustrate just how well separated and how easily identifiable the clumps are in position-velocity space. While the RMC taken as a whole has no clear central concentration of CO, the clumps in Figure 3 appear to be quite centrally condensed. The figure also illustrates that in general, the clumps are distinct, well-defined entities. The high-longitude limit of the Rosette Nebula occurs at the right-hand boundary of Figure 3 (at $l = 206°765$); it is therefore clear that the clumpiness exists independent of the dynamical effects of the H II region.

The clumps illustrated in Figure 3 are the "peas" in our model of the RMC. The mean peak ^{13}CO antenna temperature of the clumps in Figure 3 is 2.4 K and the mean one-dimensional rms velocity dispersion of the gas within the clumps is 0.9 km s^{-1} (2.2 km s^{-1} FWHM). The typical linear diameter is about 4.2 pc, implying a mean mass for the clumps in Figure 3 of $\sim 500\ M_\odot$ and a mean density of ~ 250 cm^{-3}. This mass is obtained from $\Sigma T_A^*(CO)\, dv$ and the CO/H_2 conversion of Bloemen *et al.* (1985). The mean density of the entire complex is about 30 H_2 cm^{-3} (Blitz and Thaddeus 1980), so the clumps are an order of magnitude denser than average. Some of the clumps are detectable in the CS $J = 2$–1 line, which implies still higher densities (A.A. Stark and L. Blitz, in preparation).

We have obtained low-noise spectra at the positions marked A–F in Figure 2. The CO and ^{13}CO spectra at position E are shown in Figure 4. The spectra show broad, low-intensity emission observed over the range of velocities from 4 to 20 km s^{-1} with some variation from spectrum to spectrum. The typical line strengths are ~ 200–500 mK for CO and ~ 50 mK for ^{13}CO in the broad component with considerable variation. The rms velocity dispersion of the broad component is ~ 6 km s^{-1} or about 3 times the dispersion of the clumps. The variation of the line strength and velocity dispersion of the broad component suggest that it is not homogeneously distributed within the complex. However, its presence at all six of the widely separated positions observed in the low-noise mode indicates that it pervades the entire molecular complex, particularly the volume between the clumps.

We can estimate the mass of the interclump gas by making the usual assumption that ^{13}CO column density is proportional to H_2 column density. One source of uncertainty is the excitation temperature, which is not obtainable from our data, since the interclump gas is likely to be subthermally excited. Fortunately, the result is insensitive to this parameter: for excitation temperatures between 4 K and 20 K for the broad component, we obtain mean H_2 column densities in the range 2.6–4×10^{20} cm^{-2}. Such low column densities are unusual, but by no means unique. Magnani, Blitz, and Mundy (1985) find comparable molecular column densities toward the small CO clouds they detected at high galactic latitude.

Taking the projected area of the complex to be 2.1×10^3 pc^2 (Blitz and Thaddeus 1980), the mass of the interclump gas is $\sim 10^4\ M_\odot$, about 10% of the whole complex. If the interclump gas were uniformly distributed, its density n would only be ~ 2 cm^{-3}; it is the low-density "soup" in which the peas swim. Note, however, that CO is not excited into emis-

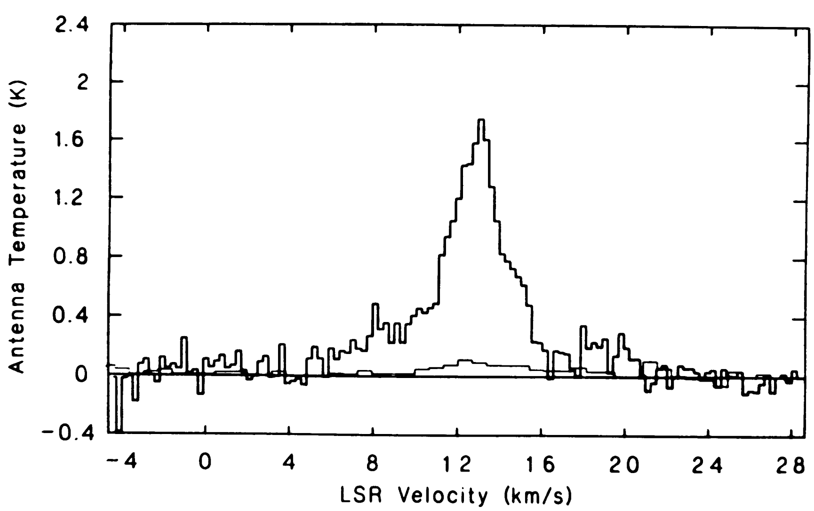

FIG. 4.—A spectrum of CO (*thick line*) and ^{13}CO (*thin line*) taken at position E shown in Fig. 2 ($l = 207°14$, $b = -2°048$). Note that both the CO and ^{13}CO emission show a broad weak feature extending over the full velocity range shown in Fig. 1. This feature is what we identify as the interclump gas or the "soup" in which the clumps are embedded. Qualitatively similar spectra are obtained at all six positions observed in the low-noise mode.

sion unless n is substantially higher than this mean value; the volume filling factor of the interclump CO line-emitting gas is thus likely to be considerably less than unity. The remaining volume could be filled with molecular gas which is too diffuse to excite CO into emission, with the atomic gas that is known to be associated with the RMC (Raimond 1966), or with ionized gas.

The velocity dispersion of the interclump molecular gas implies that it is not gravitationally bound to the complex. The virial mass of the clumps is in good agreement with the mass of H_2 implied by the integrated properties of the CO and ^{13}CO lines of $\sim 1 \times 10^5$ $M_\odot$ (Blitz and Thaddeus 1980). Since most of the mass is in the clumps, the velocity dispersion of the interclump gas exceeds the escape velocity defined by the dense gas. If the interclump gas is produced by evaporation from the clumps themselves, and if our results are representative of a steady state, the lifetime of the molecular clouds due to evaporation of molecular gas alone is no more than 10^8 yr. The dynamical effects concomitant with the formation of high-mass stars is likely to make the lifetime of the cloud complex considerably shorter (Blitz and Shu 1980). In short, our data provide evidence for pervasive molecular gas which is associated with the RMC complex but is not bound to it. This molecular material can leak out of the GMC, into the interstellar medium.

Because the interclump molecular gas is so tenuous, it does not significantly impede the motion of the clumps in the molecular cloud. The ratio of the column density of clump to interclump gas is about 10; thus a significant fraction of the momentum of a clump is lost only after ~ 10 crossing times, or $\sim 2 \times 10^8$ yr. The collisions between clumps occur about an order of magnitude faster and are therefore more important to clump dynamics. The entire giant molecular cloud can be supported by the random motion of the clumps for time scales long compared to the star formation time scales of the accompanying OB associations (Blaauw 1964). The free-fall time scale for the clumps is $\sim 2 \times 10^6$ yr, but these may be supported against collapse by magnetic fields (Mouschovias 1976*a*, *b*) or other effects.

The RMC is typical of the giant star-forming molecular clouds in the solar vicinity (Blitz 1980), and its size and mass are comparable to those found elsewhere in the Galaxy (Stark 1979; Sanders, Scoville, and Solomon 1985). Thus, it is likely that the detailed structure of the RMC is typical of most of the giant molecular clouds in the Milky Way. The results of Galactic CO surveys imply that GMCs are transitory objects (Stark 1983); we have shown here that in at least one GMC, at least some of the molecular material is leaking away.

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