THE ASTROPHYSICAL JOURNAL, 206:443–451, 1976 June 1

CO OBSERVATIONS OF NGC 1579 (S222) AND S239

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Received 1975 September 30; revised 1975 November 10

ABSTRACT

The 2.6 mm lines of ^{12}CO and ^{13}CO have been observed toward the small galactic diffuse nebulae NGC 1579 (S222) and S239. The H92α recombination line has also been detected from NGC 1579. Toward NGC 1579, we have observed evidence for self-absorption in the ^{12}CO line. For both regions, high-velocity wings and line broadening are observable in the ^{12}CO line; the features observed toward S239 suggest ordered, free-fall collapse of a localized region of the cloud onto a newborn stellar cluster. Examination of the available data suggests that NGC 1579 is both a reflection nebula (illuminated by LkHα 101), and an obscured H II region excited by a star of spectral type near B1, while S239 is a reflection nebula or a Herbig-Haro object. Our studies of these regions show that line widening in CO is at least as important an indicator of star-formation activity as enhanced line emission.

Subject headings: interstellar: molecules — nebulae: individual

I. INTRODUCTION

Recent CO observations of interstellar dust clouds (e.g., Milman *et al.* 1975*a*, *b*; Dickman 1975) have shown that interstellar clouds have temperatures $\leqslant 10$ K except near hot stars, where the temperatures may be significantly enhanced. Since dark clouds are thought to be regions of star formation, the presence of enhanced CO may be a good indication of star formation (Loren, Vanden Bout, and Davis 1973; Blair, Peters, and Vanden Bout 1975).

We have recently begun an investigation of small reflection nebulae, both with and without visible exciting stars, to investigate possible sites of star formation (Knapp *et al.* 1975, hereafter Paper I). During this investigation we found evidence for wide wings on many CO profiles, a second possible indicator of star formation activity (Loren *et al.* 1974; Kutner and Tucker 1975). Such line wings appear to arise from two different causes; systematic collapse of part of a cloud, and more random expansion motions about a newly formed H II region. Two objects (S239 and NGC 1579) were partially mapped in the CO line and appear to represent an example of each case: a detailed discussion of the regions is given in this paper.

* Operated by Associated Universities, Inc., under contract with the National Science Foundation.

II. OBSERVATIONS

The observations of the $J = 1 \rightarrow 0$ transitions of the ^{12}CO and ^{13}CO molecules were made in 1975 March, with the 11 m NRAO telescope at Kitt Peak, Arizona, and are described more fully in Paper I. The spatial resolution was $\sim 65''$ and the velocity resolution ~ 0.26 km s^{-1}. Position-switching was used for all the observations, with integration times of 15 min per point.

The regions were partially mapped at a spacing of $1'$ in the ^{12}CO line, and two points in each were also observed in the ^{13}CO line. The line intensities were expressed in terms of the Rayleigh-Jeans brightness temperature

$$T_A{}^* = \frac{h\nu}{k}\{\mathfrak{F}(T_B) - \mathfrak{F}(T_{\mathrm{bb}})\}\,, \tag{1a}$$

where

$$\mathfrak{F}(T) = \left[\exp\left(\frac{h\nu}{kT}\right) - 1\right]^{-1}, \tag{1b}$$

T_B is the brightness temperature of the line, and T_{bb} the temperature of the microwave background, taken as 2.7 K. The central positions observed for each object were the following:

NGC 1579: $l = 165\overset{\circ}{.}4$, $b = -9\overset{\circ}{.}0$, $\alpha(1950) = 04^{\mathrm{h}}26^{\mathrm{m}}59\overset{\mathrm{s}}{.}0$, $\delta(1950) = +35°10'00''$.

S239: $l = 178\overset{\circ}{.}9$, $b = -20\overset{\circ}{.}1$, $\alpha(1950) = 04^{h}28^{m}25\overset{s}{.}0$, $\delta(1950) = +18^{\circ}00'51''$.

The observed line profiles are presented in Figures 1–4. In Figure 1 are shown the observed ^{12}CO profiles for NGC 1579; in Figures 2*a* and 2*b* the ^{12}CO and ^{13}CO profiles at the position of LkHα 101 and 1′ N of this position; in Figure 3 the grid of observed ^{12}CO profiles for S239, and in Figures 4*a* and 4*b* the ^{12}CO and ^{13}CO profiles observed at the center of S239 (point C) and 2′ E (point 2E) of the position.

III. NGC 1579 (LkHα 101)

This region is of particular interest because it contains the very luminous emission-line star LkHα 101 (Herbig 1956). LkHα 101 has a very high infrared flux (Cohen and Woolf 1971), bright Hα emission lines (Herbig 1956), and a detectable radio flux (35 mJy at 4 cm wavelength [Spencer and Schwartz 1974]), all suggesting that it is a highly luminous pre–main-sequence star. On the basis of its visible (Allen 1973) and near-infrared (Herbig 1971) spectrum, the object has been classified as of spectral type F8 IIe (Allen 1973); and it is generally believed to be the highly reddened illuminating star of NGC 1579. The star appears to be projected on one of the prominent dust lanes running across the face of the nebula.

However, the nature of NGC 1579 itself is rather ill-defined. It has been classified as a reflection nebula by Herbig (1956) on the basis of its spectrum, which closely resembles that of LkHα 101 and shows emission lines only of Fe II and H II, and as an H II region by Sharpless (1959) on the basis of its red color (it is number 222 on Sharpless's list). Photographs of the region (e.g., the Palomar Observatory Sky Survey Prints, and Fig. 1 of Herbig 1971) show it as a small, bright nebula, crossed by several obscuring dust lanes, at the end of a long ($\gtrsim 3°$), narrow dust lane. (This phenomenon of small regions of star formation activity appearing at the end of dust lanes is fairly common; other examples are IC 5146 and the BM Andromedae complex [Aveni and Hunter 1969].)

On the other hand, searches for continuum emission from this region have produced contradictory results. Felli and Churchwell (1972) detected weak, extended emission in this region at 1.4 GHz, including a source of angular size $\lesssim 5'$ and strength ~ 2 Jy at the position of NGC 1579. However, searches at 15 GHz by Churchwell, Felli, and Mezger (1969) and 2.7 GHz by Churchwell and Felli (1970) yielded no continuum at this point above ~ 0.5 Jy. Because the nature of NGC 1579 is important to a general understanding of the region and to our interpretation of the CO observations, we have carried out continuum and hydrogen recombination line observations of this region using the sensitive facilities available at the Deep Space Network, Goldstone, California.

These observations were made on 1975 September 3, with the 64 m antenna. Flux measurements were made at the position of LkHα 101, using ON-OFF measurements, at 2.3 and 8.3 GHz, and line measurements of H92α emission at 8.3 GHz. The zenith system temperatures at 2.3 and 8.3 GHz were, respectively, 18 and 22 K, the beamwidths $\sim 8\overset{'}{.}1$ and $2\overset{'}{.}5$, and the spectral line observations were made with a 64-channel autocorrelator, using a total bandwidth of 4 MHz (~ 2.3 km s^{-1} per channel). The results for the H92α line are as follows: $T_L = 0.014 \pm 0.002$ K, $T_c = 0.108 \pm 0.02$, $v_c = +3.08 \pm 1.23$ km s^{-1}, and $\Delta v = 17.52 \pm 3.45$ km s^{-1}, where the symbols have their usual meanings. The measured fluxes are as follows: $S(2.3 \text{ GHz}) = 0.18$ Jy; and $S(8.3 \text{ GHz}) = 0.20$ Jy. These results show clearly the following: there is a compact H II region near LkHα 101, of angular diameter $\lesssim 2\overset{'}{.}5$, since the fluxes measured with beams of size 8′ and $2\overset{'}{.}5$ are the same.

By comparing the H92α line strength with that of the continuum, we find the LTE electron temperature of the region, T_e^*, to be 8300 ± 1500 K. The line width, Δv, also yields a firm upper limit to the kinetic temperature of the region, T_k, of 6600 ± 2500 K. The excitation parameter of the region is given by

$$U = 13.3\left(\frac{\nu}{\text{GHz}}\right)^{0.03}\left(\frac{T_e}{10^4}\right)^{0.12}\left[\left(\frac{D}{\text{kpc}}\right)^2\left(\frac{S}{\text{Jy}}\right)\right]^{1/3} \quad (2)$$

(Churchwell and Walmsley 1973), where D, the distance, is ≥ 800 pc (Herbig 1971), and has a value for NGC 1579 of $U \geq 7.2$. Using the average stellar parameters of Panagia (1973), we see that this value corresponds to that for a star of type B0.5 V or B1 II. We can now calculate the mass of hydrogen in the H II region from its angular size. We know from our single-dish measurements that the H II region is $\lesssim 2\overset{'}{.}5$ in diameter. Interferometer measurements, on the other hand, show that about half of the flux of this H II region is within a diameter of $\sim 1\overset{'}{.}5$ (Brown, Broderick, and Knapp 1975). Thus the region is $\sim 2'$, the electron density ~ 100 cm^{-3}, and the hydrogen mass $\sim 0.1\ \mathfrak{M}_\odot$.

Our CO observations of NGC 1579 are presented in Figure 1, with the position of LkHα 101 indicated. There is a lot of relatively high-velocity structure, extending between velocities of ~ -10 to $+14$ km s^{-1}, irregularly distributed with position, so that we are not seeing systematic motions about some common center. This high-velocity structure does not represent a single entity as is the case with S239 (§ IV), so it does not allow of an analytic treatment.

The brightest CO profile is seen at the position of LkHα 101. The falloff of the CO intensity suggests that the heated region is $\sim 2'$–$3'$ in diameter, and is therefore probably heated by the small obscured H II region.

A most interesting aspect of the CO line profiles shown in Figure 1 is the self-absorption feature seen at ~ 0 km s^{-1} around the position of LkHα 101. This is clearly illustrated in Figures 2*a* and 2*b*, which show the ^{12}CO and ^{13}CO profiles observed at the position of LkHα 101 and 1′ N, and is particularly striking for the point 1′ N (Fig. 2*b*). This self-absorption may be partly responsible for the fact that enhanced ^{12}CO emission is not seen over a wider range in position (Fig. 1). The distribution of the dip agrees quite well

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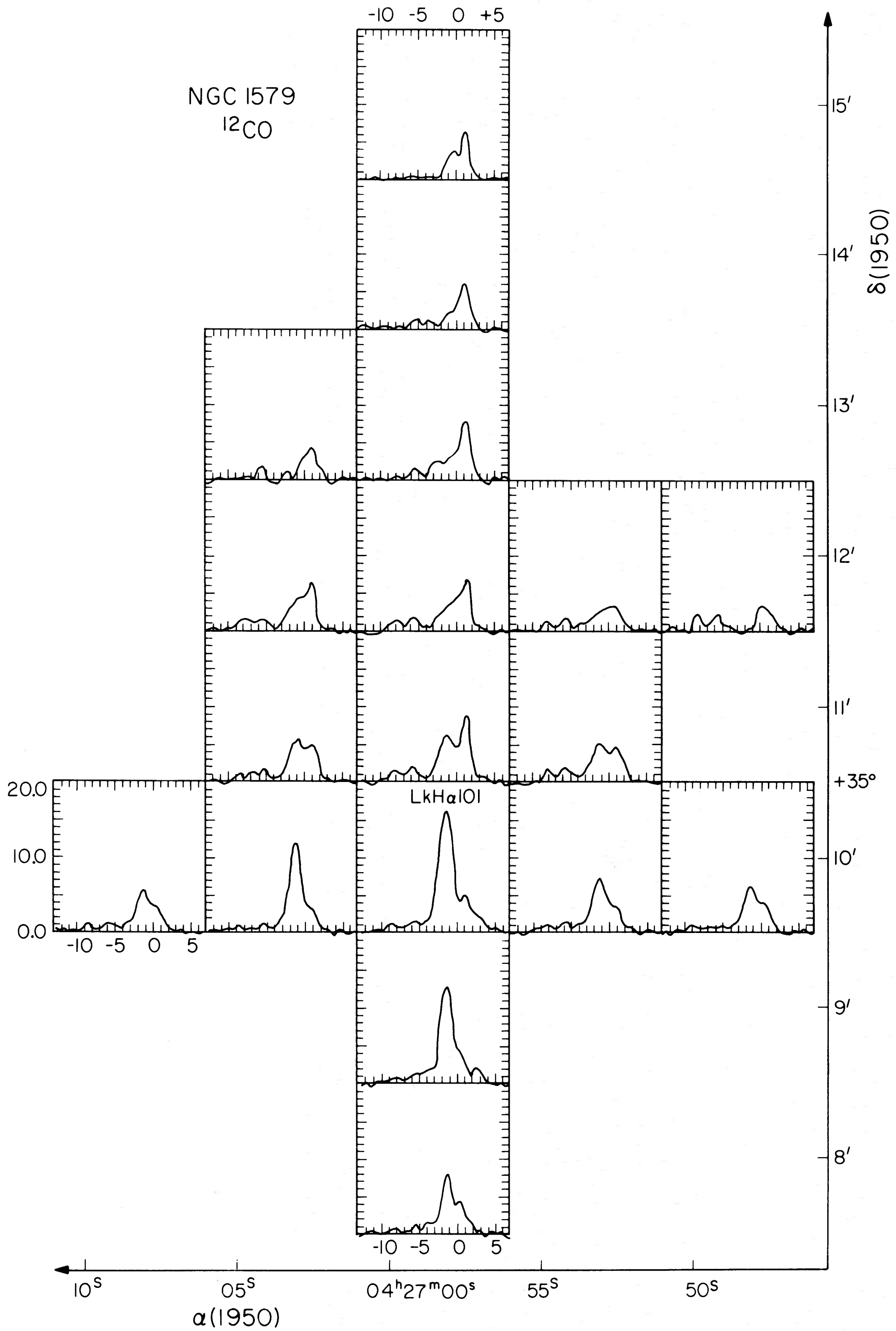

FIG. 1.—^{12}CO profiles observed toward NGC 1579, with their positions on the sky. The ordinate is equivalent brightness temperature, the abscissa radial velocity with respect to the local standard of rest. The profile observed at the position of LkHα 101 is indicated.

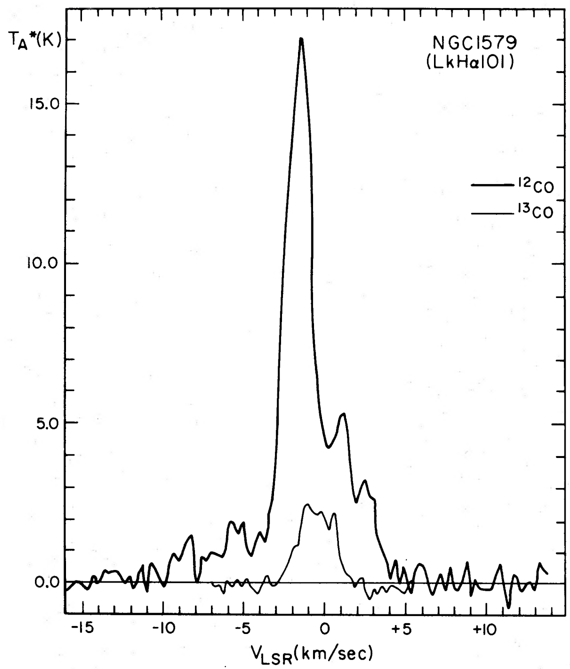

FIG. 2*a*

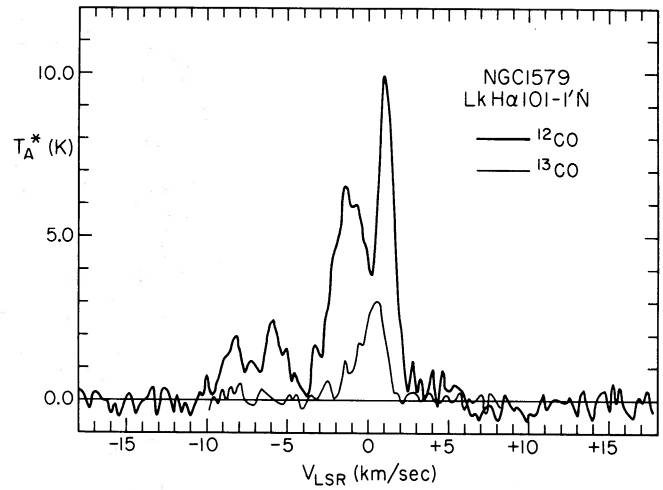

FIG. 2*b*

FIG. 2.—^{12}CO and ^{13}CO profiles observed at (*a*) the position of LkHα 101 and (*b*) 1′ N of this position, in the direction of NGC 1579.

with the distribution of dust lanes (see Fig. 1), and the presence of self-absorption in NGC 1579 is therefore not surprising because foreground dust lanes are seen across the face of a hotter cloud. The ^{12}CO brightness temperature inside the self-absorption dip (Fig. 2*b*) confirms the generally low value of the excitation temperature in dark clouds.

The mass of the dark cloud region around NGC 1579 may be estimated from its apparent angular diameter ($\sim 25'$) assuming a density of hydrogen molecules of 10^3 cm^{-3} (we cannot use the CO observations to estimate the density because of the presence of self-absorption). The mass of the cloud is then $\sim 10^4$ $M_{\odot}$.

The present observations then show the following: that NGC 1579 is a reflection nebula illuminated by LkHα 101, and also contains a compact H II region. This could either be a small ionized region surrounding a star of spectral type near B1, or, more likely because of its low mass (0.1 $M_{\odot}$), could consist of gas out-flowing from the envelope of LkHα 101. In all respects this H II region has properties similar to those of other galactic H II regions, including its electron temperature (~ 8000 K). This value is much lower than that suggested for the envelopes of other emission-line stars by Rydgren, Strom, and Strom (1976).

IV. SHARPLESS 239

S239 is a diffuse red nebula on the face of a small dust cloud, and has been classified as an H II region by Sharpless (1959). However, no radio continuum was detected (Felli and Churchwell 1972), leading Felli and Perinotto (1974) to classify the object as a planetary nebula. Strom *et al.* (1974) have named this region as a giant Herbig-Haro object (No. 102), with an emission-line spectrum (indicating radial velocities of -55 km s^{-1}) over its whole extent. No visible star or stars appear to illuminate S239, and no infrared source at this position is listed in the Two-Micron Sky Survey (Neugebauer and Leighton 1969).

The small dark cloud containing S239 also appears to be a region of star-formation activity; it contains three smaller Herbig-Haro objects (Herbig 1974) and the Orion-population stars XZ Tau and HL Tau. The cloud has an appreciable column density of gas: H_2CO (Dieter 1974) and OH and H I (Knapp 1972) have been observed.

No direct distance determination has been made for this cloud. Two indirect estimates of the distance are available, and one estimate may be made from the fact that the cloud appears to be in the middle of the Hyades, whose parallactic distance (e.g., Upgren 1974) is 45 pc. A second estimate is possible because the cloud is one of a small string of similar clouds, one of which contains T Tau, whose distance has been found by Kuhi (1964) to be 170 pc. In view of the agreement in radial velocity between the clouds containing S239 and T Tau (see Paper I), the higher distance may be more likely.

Our CO observations of this region are presented in Figures 3, 4, and 5. The ^{12}CO observation of the central region of the nebula shows immediately that two components are present, a localized component with a large velocity dispersion and a more widespread,

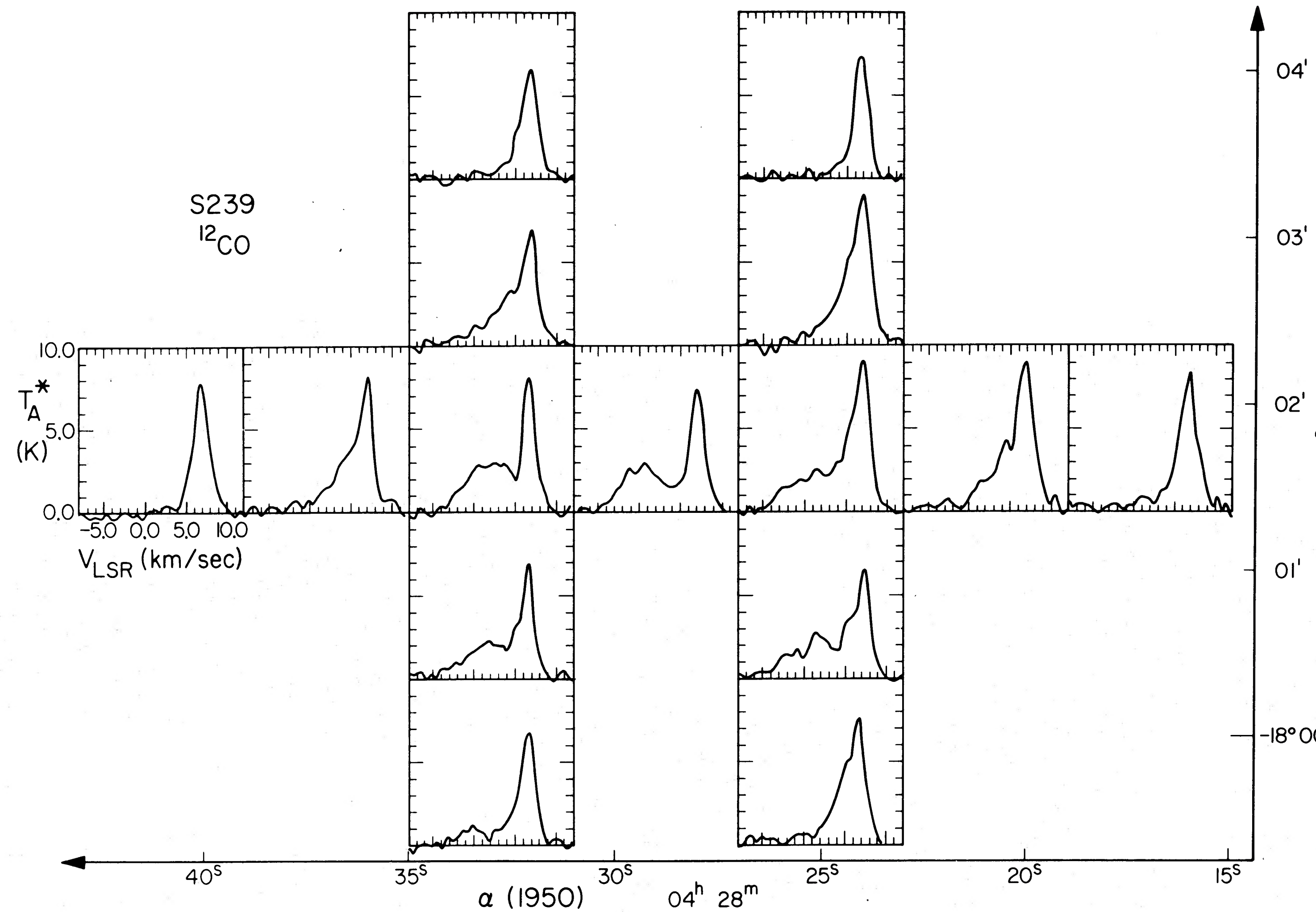

FIG. 3.—^{12}CO profiles observed toward S239

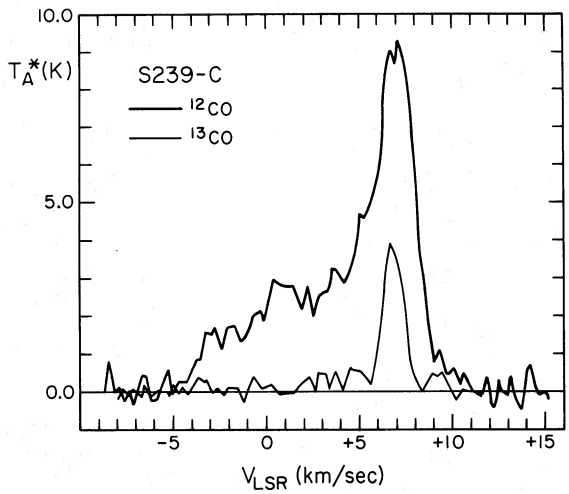

FIG. 4a

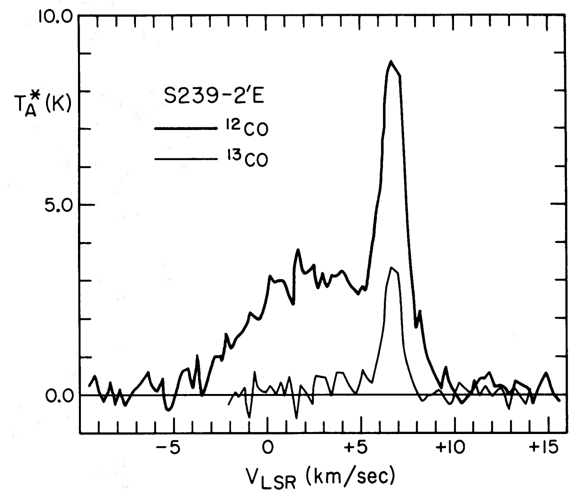

FIG. 4b

FIG. 4.—^{12}CO and ^{13}CO profiles observed at (*a*) $\alpha = 04^h28^m25^s$ (point C) and (*b*) $\alpha = 04^h28^m33^s$ (point 2E) ($\delta = +18°10'$) toward S239.

brighter, low-velocity-width component. The latter presumably arises from the dust cloud, as is shown by our CO observation taken at a point $\sim 9'$ from S239 (Fig. 5), and its central velocity agrees very well with that of the other molecules observed for this cloud. The dust-cloud CO has a somewhat higher temperature at the position of S239, perhaps due to local heating at this position.

a) *Mass of the Dust Cloud*

The quantities T_{01}, the CO excitation temperature, and N_{CO}, the column density, may be derived from the usual formulae (see, e.g., Paper I); at position C in S239 we have $T_{01} = 12.4$ K and $N_{CO} = 7 \times 10^{17}$ cm^{-2} (assuming $^{12}C/^{13}C = 89$). However, recent theoretical

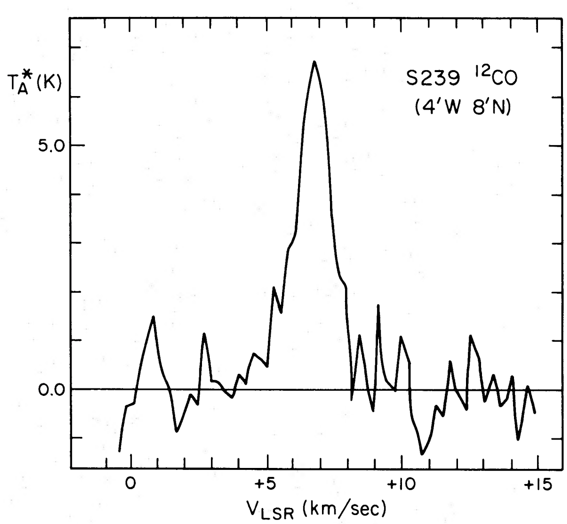

FIG. 5.—^{12}CO profile observed 4′ W, 8′ N of the center of S239.

(Leung and Liszt 1975) and observational (Encrenaz *et al.* 1975; Knapp *et al.* 1975) studies show that only about 10 percent of the C is in the form of CO, so that the corresponding hydrogen column density is then likely to be $\geqslant 10^{22}$ H_2 mol cm^{-2}. The cloud has a radius of $\sim 17'$, so that $10^4 \geqslant n(H_2) \geqslant 2.5 \times 10^{-3}$, while $20\,\mathfrak{M}_\odot \leqslant \mathfrak{M} \leqslant 300\,\mathfrak{M}_\odot$ (depending on the distance).

b) *Localized Large-Velocity Dispersion Component*

We can see from Figure 3 that the wide component is confined to a region $\sim 5'$ (EW) by $3'$ (NS). Its regular shape and variation with position suggest ordered, rather than turbulent, motions, in contrast to the situation in NGC 1579. We describe here a tentative, simple model of the region as an expanding, or contracting, spherical gas cloud, optically thick in the ^{12}CO line. This model is similar to the uniform radial flow model for IRC +10216 (Morris 1975; Kuiper *et al.* 1976) and to that for the Orion Kleinmann-Low nebula (Kuiper, Zuckerman, and Kuiper 1975).

c) *Model Contracting Cloud*

Suppose we have an isothermal sphere of radius R undergoing spherical contraction (or expansion) with velocity

$$V(r) = V_0\left(\frac{r}{R}\right)^\alpha , \tag{3}$$

where r is the radial distance from the center of the cloud, and $V(r) = V_0$ at $r = R$. For an optically thick line, the observed antenna temperature is

$$\frac{T_A(V_z)}{T_x} = [1 - \exp(-y_m)] , \tag{4}$$

where

$$y_m = 4 \ln 2\, p_m{}^2/B^2 , \quad \text{and} \quad T_x = \mathfrak{F}(T_{01}) .$$

Here V_z is the component of velocity along the line of sight z, B is the full half-power beamwidth of the telescope (where the beam is assumed to be Gaussian and centered on the source), and p_m is the maximum value of p (the projected distance from the center of the cloud) at which V_z is observed. Then

$$\frac{p_m(V_z)}{R} = f(\alpha)\left(\frac{V_z}{V_0}\right)^{1/\alpha} \qquad (5a)$$

where

$$f(\alpha) = (-\alpha)^{1/2}(1 - \alpha)^{(1-\alpha)/2\alpha} \qquad (5b)$$

for $\alpha < 0$ and $p/R \leq [-\alpha/(1 - \alpha)]^{1/2}$. For p/R greater than this value

$$\frac{P_m(V_z)}{R} = \left[1 - \left(\frac{V_z}{V_0}\right)^2\right]^{1/2}. \qquad (5c)$$

For $\alpha \geq 0$, $p_m(V_z)/R$ is given by equation (5c) for all values of V_z. Note that, for $\alpha > 0$, the highest velocities relative to the line center arise in directions passing close to or through the center of the cloud. For $\alpha \gg 0$ and an optically thick line, we can see qualitatively that the shape and velocity range of the line profile are determined only by B/R, T_x, and V_0. When $R \ll B$, the profile shapes are parabolic, with full width (at $T_A = 0$) of $2V_0$.

Although S239 is resolved, the shapes of the wings are clearly not parabolic (Figs. 3 and 4) showing that $\alpha < 0$ for this cloud. We can find α as follows: for small p_m, equation (4) leads to $T_A \approx V_z^{-2/\alpha}$, and thus α may be found directly by examining the profile wings in a log-log plot of T_A^* versus V. This procedure was carried out for S239, point 2′ E (which appears to be close to the center of the distribution). Apart from the perturbation caused by the dust cloud emission, both sides of the line have a slope corresponding to $\alpha = -0.5 \pm 0.1$.

The value of the boundary velocity, V_0, may be found from the line width, from

$$\Delta V_z = 2V_{1/2} = 2V_0\left[\frac{B}{2f(\alpha)R}\right]^\alpha. \qquad (6)$$

For S239 2′ E, ΔV_z is 9.7 ± 1 km s^{-1}, where most of the uncertainty is due to the presence of the dust-cloud emission. Hence $V_0 = 3.9$ km s^{-1}; and we estimate $T_x = 3.2$ K, and the central velocity of the profile V_c to be $+3$ km s^{-1}. The model profile with the parameters derived above is plotted for S239 2′ E, with the observed data points, in Figure 6.

A confirmation of the value for α comes from a plot of the line width versus position. We have plotted $\Delta V'$, the width along the base of the line ($=2V_z$[max]) as a function of position. We have three cuts across S239 (one in α, two in δ); these plots are shown in Figure 7. All of the slopes in this figure are roughly the same, and again correspond approximately to $\alpha = -\frac{1}{2}$.

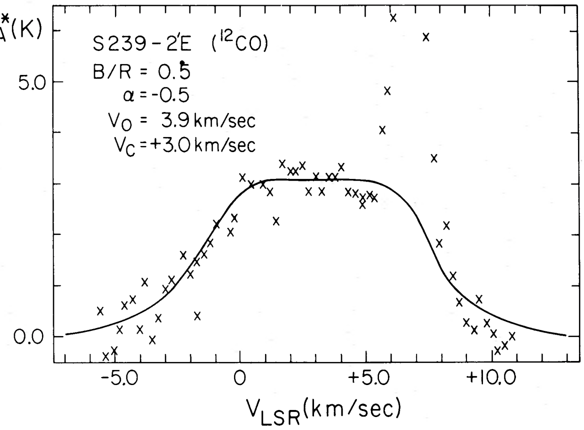

FIG. 6.—T_A^* versus V for the ^{12}CO observations of S239 2′ E.

The above model describes the CO line shapes observed in this cloud reasonably well, with a minimum number of assumptions; however, we have little direct observational evidence to support these assumptions—namely, that the cloud is optically thick and isothermal. The assumption of optical thickness is probably reasonable because of the size of the region; whether or not the gas is isothermal cannot be decided without further observations.

The wide velocity component may not be adequately described by this simple model, since (a) the region appears to be somewhat elongated, and (b) the central velocity of the broad feature appears to vary between ~1 and 4 km s^{-1} with position. Thus other effects (nonradial motions, rotation, temperature inhomogeneities) may be present. However, their effect may be small compared with the effects discussed above; construction of a more detailed model must await further data.

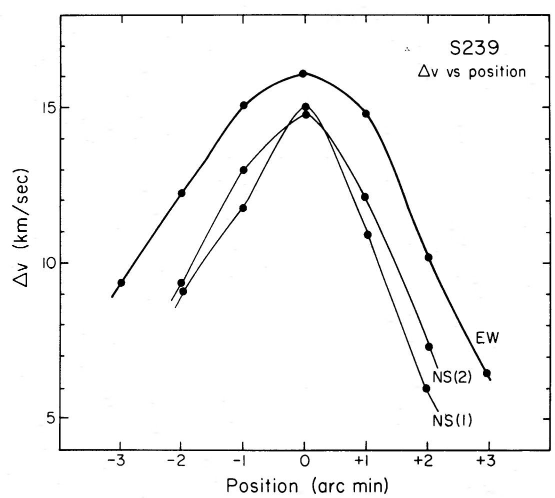

FIG. 7.—The total line width $\Delta V'$ versus position for S239. The two north-south cuts are through points C (No. 1) and 2′ E (No. 2).

Observations of the type described above are able to yield no information about whether the cloud is expanding or collapsing. However, expansion probably requires the agency of some energetic central object, of which there is (so far) no observational evidence. If we may assume that the cloud is contracting, we note that the derived dependence of velocity on radial distance ($\Delta V \approx r^{-1/2}$) corresponds to the free fall of gas onto some central condensed object, a situation described by Larson (e.g., 1969) for the later stages of protostellar collapse. The mass of the central object may then be calculated from

$$M = 1.16 \times 10^2 V_0{}^2 R\,, \tag{7}$$

where M is the mass of the central object in $\mathfrak{M}_\odot$, R is now in parsecs, and V_0 is in km s^{-1}. Taking the radius of the region to be 2′, we have $50\,\mathfrak{M}_\odot \leq \mathfrak{M} \leq 180\,\mathfrak{M}_\odot$ depending on the distance (with the higher mass value being more likely). This mass estimate is very reasonable for a small cluster of stars, whose most massive member is likely to be no earlier than types B1 or B2. Thus we may have at present ~ 50 percent of the total mass of this cloud collapsing into stars. The free-fall time for this part of the cloud is $\sim 10^3$ years.

If we assume that all of the mass is concentrated within a region $\leqslant 1'$ in size, the mean density of the core is about $n(H_2) \geqslant 5 \times 10^7$ cm^{-3} at the larger distance. Thus further observations of this region of molecules sensitive to high densities (CS, SO, etc.) should be made to confirm the presence of a dense concentration in the cloud. Also, a search for infrared objects, and for the source of illumination of S239, would be very valuable. As noted previously, this cloud is one of a small string of dark clouds, among which is that containing T Tau (see Paper I); it is possible that all of these clouds are the result of a recent disturbance and may have fragmented from a larger cloud (e.g., after the passage of a galactic shock wave, as described by Woodward 1975), and all may contain objects in the very earliest stages of star formation.

V. DISCUSSION AND CONCLUSIONS

The two regions described in this paper appear to be examples of two different kinds of objects, and may be compared and contrasted. Both appear to be active regions of star formation which are parts of larger clouds, and the available observations are consistent with star formation taking place in two regions of comparatively small total mass, with up to half of the cloud mass being involved. S239 appears to be at a much earlier stage than does NGC 1579 (which has already developed a compact H II region), with the ordered collapse motions in the former cloud giving way to the more chaotic motions in the latter.

The observations of these regions reinforce the point made in Paper I that wide wings on the CO line are at least as important an indication of star formation activity as enhanced CO emission; neither of the present regions is particularly striking in this latter respect. Further observations of these clouds, especially in the lines of high-dipole-moment molecules, would be invaluable for determining the density and temperature structure in these and similar regions, and may afford the opportunity of forming an observational picture of the very earliest stages of star formation. The comparative simplicity of the types of region observed here and in Paper I should make the interpretation relatively straightforward.

We would like to thank Dr. A. S. Milman for help with reading the data tape, and Dr. K. Marsh for suggesting observations of LkHα 101. We are grateful to the National Radio Astronomy Observatory and the Deep Space Network for the observing time for this project, and their staffs, especially Dr. B. L. Ulich, for their help in carrying it out. We thank Drs. M. Morris and K. Y. Lo for valuable discussions. Research at OVRO is supported by the National Science Foundation under grant GP-30400-X1, and by the Office of Naval Research under contract number N00014-67-A-0094-0019. This paper presents the results of one phase of the research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract number NAS7-100.

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