

CARBON MONOXIDE OBSERVATIONS OF R MONOCEROTIS, NGC 2261, AND HERBIG-HARO 39: THE INTERSTELLAR NOZZLE

J. CANTÓ, L. F. RODRÍGUEZ, J. F. BARRAL, AND P. CARRAL
 Instituto de Astronomía, Universidad Nacional Autónoma de México
Received 1980 July 9; accepted 1980 August 28

ABSTRACT

R Mon is a peculiar star located at the apex of the (apparent) cometary nebula NGC 2261. Carbon monoxide observations of this region show an elongated ($\sim 4' \times 2'$ or $\sim 0.8 \times 0.4$ pc) molecular cloud at whose center lies R Mon. The interpretation of the observations suggests that the cloud is disk shaped and that the stellar wind of R Mon has created a bipolar cavity in it. In the visible, the northern cavity (NGC 2261) shines by reflecting the light of R Mon. The southern cavity is obscured in the visible by the tilted molecular disk but can be detected in the CO observations. We found a blueshifted CO component related to the northern lobe (NGC 2261) and a redshifted CO component related to the obscured southern lobe. Thus, NGC 2261 is not a cometary nebula but one of the lobes of a bipolar nebula. The wind of R Mon is being channeled by the cavities into two antiparallel annular streams. An appreciable fraction of the mechanical energy of the wind is carried out in the streams. At $\sim 7' (\sim 1.4$ pc) to the north of R Mon the northern stream encounters another small molecular cloud. In this interaction the stream is deflected and shocks against itself. Upon cooling it radiates as HH 39.

These results suggest that a recently formed, wind-producing star located in a disklike molecular environment (an interstellar disk) will have its wind channeled into two opposite directions along the poles of the disk. These collimated streams can travel over considerable distances (several pc) in the low-density interstellar medium and probably are the energy source of Herbig-Haro objects. The anisotropic mass outflows discovered recently in some regions of star formation could be due to the same phenomenon, although driven by more powerful winds.

Subject headings: hydrodynamics — nebulae: individual — nebulae: reflection —
 radio sources: lines — stars: individual — stars: pre-main-sequence

1. INTRODUCTION

The bright cometary nebula NGC 2261 has been observed since the times of Sir William Herschel. At the apex of the nebula there is a semistellar ($\sim 5''$) condensation, R Mon, whose light variations were first reported by Schmidt (1861). These variations are irregular and occur over a range of at least 4 mag. The spectra of R Mon and NGC 2261 taken by Slipher (1912) were very similar and indicated a reflection nature for the nebula. Photographs taken by Hubble (1916) showed that the outline of NGC 2261 undergoes marked changes within a period of a few months. Since then NGC 2261 is often referred to as Hubble's Variable Nebula.

Even though R Mon has been studied photometrically and spectroscopically several times, there is no consensus on its spectral type. Joy (1945) mentions that the spectrum of R Mon corresponds closely with those of T Tauri variables and classifies it as a Ge-type star. However, Herbig (1968) points out that "there is no convincing evidence in the spectrum of R Mon of the presence of a G- or K- type star." Herbig also mentions

in his paper that in 1946 when R Mon rose to about 10 mag, "the spectrum was superficially like that of an early A-type supergiant, but the extreme sharpness of the higher Balmer lines suggests a shell."

More recently, Imhoff and Mendoza (1974) assume R Mon to be an A5 supergiant on the basis of a spectrogram taken by Mendoza (1970). When Mendoza (1966) discovered the infrared excesses in T Tauri stars, R Mon was one of the objects in his list. The spectrum of R Mon peaks at about $3 \mu\text{m}$, and from infrared observations Imhoff and Mendoza (1974) estimate its total luminosity to be $\sim 660 L_{\odot}$.

NGC 2261 extends about $3'$ north of R Mon. Duncan (1956) published several of the photographs obtained by C. O. Lampland. From 1916 to 1951 the nebula was frequently photographed by Lampland, who accumulated 940 plates. These plates show the remarkable changes that can occur in the nebula on a time scale of months. Lampland himself (1926) was unable to establish any periodicity in the variations. On the other hand, he concluded that the apparent changes were not due to actual displacements but to reflection of the

variable light from R Mon since the apparent motions were always away from the star. Lampland (1931) reports rates of apparent motion as high as $1/4''$ a day. If we take this rate of motion as due to a pulse of light traveling perpendicular to the line of sight, we derive a distance of ~ 700 pc, in agreement with the value of 690 pc determined spectroscopically (Johnson 1968) for the star cluster NGC 2264 located about 1° north of R Mon.

Another interesting object in the region was first noticed by Herbig (1968). About $4'$ beyond the farthest extension of NGC 2261 and almost on its axis of symmetry there is a Herbig-Haro object, HH 39. Herbig suggested that the HH object should be related to NGC 2261 because it is so near to the axis of the nebula and because there are no other peculiar objects in the area. A possible relationship between R Mon, NGC 2261, and HH 39 was proposed again by Cantó and Rodríguez (1980).

To investigate the nature of these objects and to search for a relationship between them, we did carbon monoxide observations of the region. These observations showed that R Mon lies at the center of a small, elongated molecular cloud. We suggest that the wind of R Mon has created a bipolar cavity whose axis is perpendicular to the plane of the cloud. The cavity focuses the wind of R Mon into two antiparallel annular streams. After traveling ~ 1.4 pc, in the low-density interstellar medium, the northern stream interacts with another small molecular cloud; the Herbig-Haro object 39 results from this interaction. In § II we describe and discuss the observations, while in the § III we discuss the phenomenon of bipolar mass outflow in regions of star formation. Finally, in § IV we summarize our results.

II. OBSERVATIONS AND DISCUSSION

The observations were made with the 11 m radio telescope of the National Radio Astronomy Observatory¹ during 1980 March 3–6. At the frequency of the $J=1\rightarrow 0$ rotational transition of ^{12}CO the antenna half-power beamwidth is $66''$. As receivers we used the NRAO 80–120 GHz cooled mixers with orthogonal polarizations. The observations were made without a sideband rejection filter and were calibrated using the chopper vane method described by Ulich and Haas (1976). The spectrometer consisted of two filter banks in a parallel-parallel configuration ($2 \times 128 \times 100$ kHz and $2 \times 128 \times 250$ kHz). Each receiver fed one-half of each filter bank, and the halves of each filter bank were averaged to improve the signal-to-noise ratio by $\sqrt{2}$. This resulted in two spectra for each position observed; the spectrum from the 250 kHz filter bank covered 83

km s^{-1} at 0.65 km s^{-1} resolution, and the spectrum from the 100 kHz filter bank covered 33 km s^{-1} at 0.26 km s^{-1} resolution. From pointing checks on Jupiter we estimate the rms pointing accuracy of our results to be about $15''$. The observations were made by averaging 6 to 10 pairs of 30 s integrations on the source minus a reference position, $\alpha(1950) = 06^{\text{h}}32^{\text{m}}20^{\text{s}}.0$; $\delta(1950) = 08^\circ46'57''$. This reference position was determined by us to be free of ^{12}CO emission to a 4σ upper limit of ~ 0.4 K. At the positions of interest we averaged several observations. The center position of our observations was at R Mon $\alpha(1950) = 06^{\text{h}}36^{\text{m}}26^{\text{s}}$; $\delta(1950) = 08^\circ46'57''$ (Herbig and Rao 1972), and the other positions are referred to by their offsets in right ascension and declination with respect to the center position, $(\Delta\alpha, \Delta\delta)$ given in units of $30''$.

Previous ^{12}CO observations in the direction of R Mon showed the existence of an associated molecular cloud (Wilson, Schwartz, and Epstein 1973; Loren, Vanden Bout, and Davis 1973; Arny and Bechis 1980). We mapped this cloud at intervals of $30''$ in ^{12}CO (see Fig. 1) to determine its spatial location and extent, as well as to search for evidence of interaction between the stellar wind of R Mon and the surrounding molecular gas. To investigate the relationship between R Mon and HH 39 we sampled at an interval of $120''$ the region between them (see Fig. 1). There was no detectable ^{12}CO emission between NGC 2261 and HH 39 to a 4σ upper limit of ~ 1 K, but related to HH 39 we detected another small molecular cloud. This cloud was mapped at $60''$ intervals. In Figure 2 we show the corrected antenna temperature (T_A^*) contours for the R Mon cloud and for the HH 39 cloud superposed on an optical photograph kindly provided by Dr. J. Meaburn. The photograph is an enlargement of a plate taken with the Science Research Council 1.2 m Schmidt with a 5-hour exposure and through a mosaic (16×16 inch) filter centered on $\text{H}\alpha + [\text{N II}]$ (Meaburn 1978). The T_A^* values shown in Figure 2 are at the estimated mean velocity of each cloud; 9.4 km s^{-1} for the R Mon cloud and 7.5 km s^{-1} for the HH 39 cloud. In the following sections we will discuss separately (a) the cloud associated with R Mon, (b) the cloud associated with HH 39, and (c) the relationship between R Mon, NGC 2261, and HH 39.

a) The Molecular Cloud Associated with R Mon

This molecular cloud is elongated and has its major axis almost perpendicular to the axis of symmetry of NGC 2261. To the west it has a maximum in T_A^* , which coincides in projection with the indentation on the west side of NGC 2261 that is clearly shown in the optical part of Figure 2, and in several photographs of NGC 2261 (cf. Johnson 1966).

At the position of NGC 2261 there is a bending in the T_A^* contours (Fig. 2). Since the bending has a scale

¹The NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

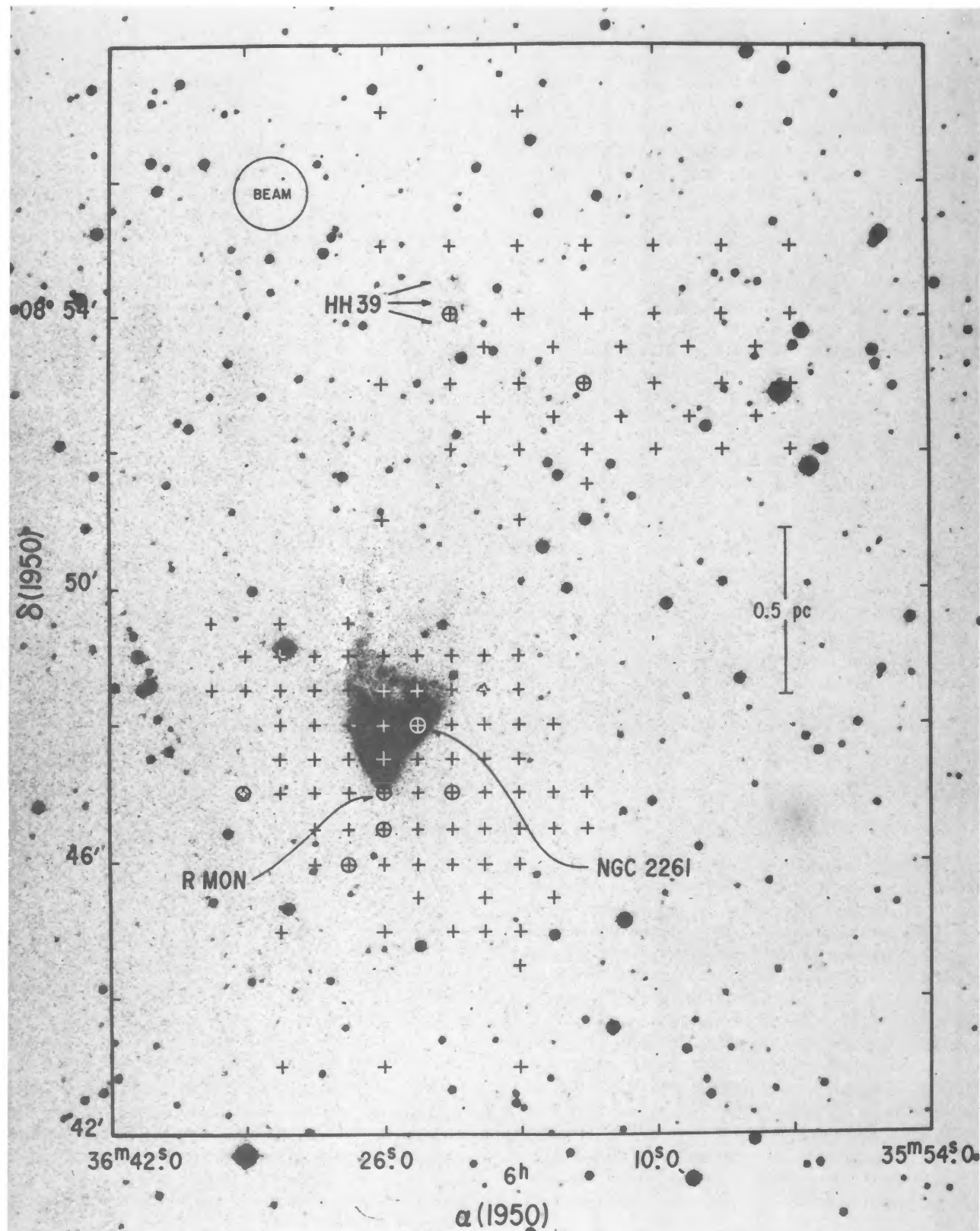


FIG. 1.—Positions mapped in ^{12}CO (+) and in both ^{12}CO and ^{13}CO ($\oplus$).

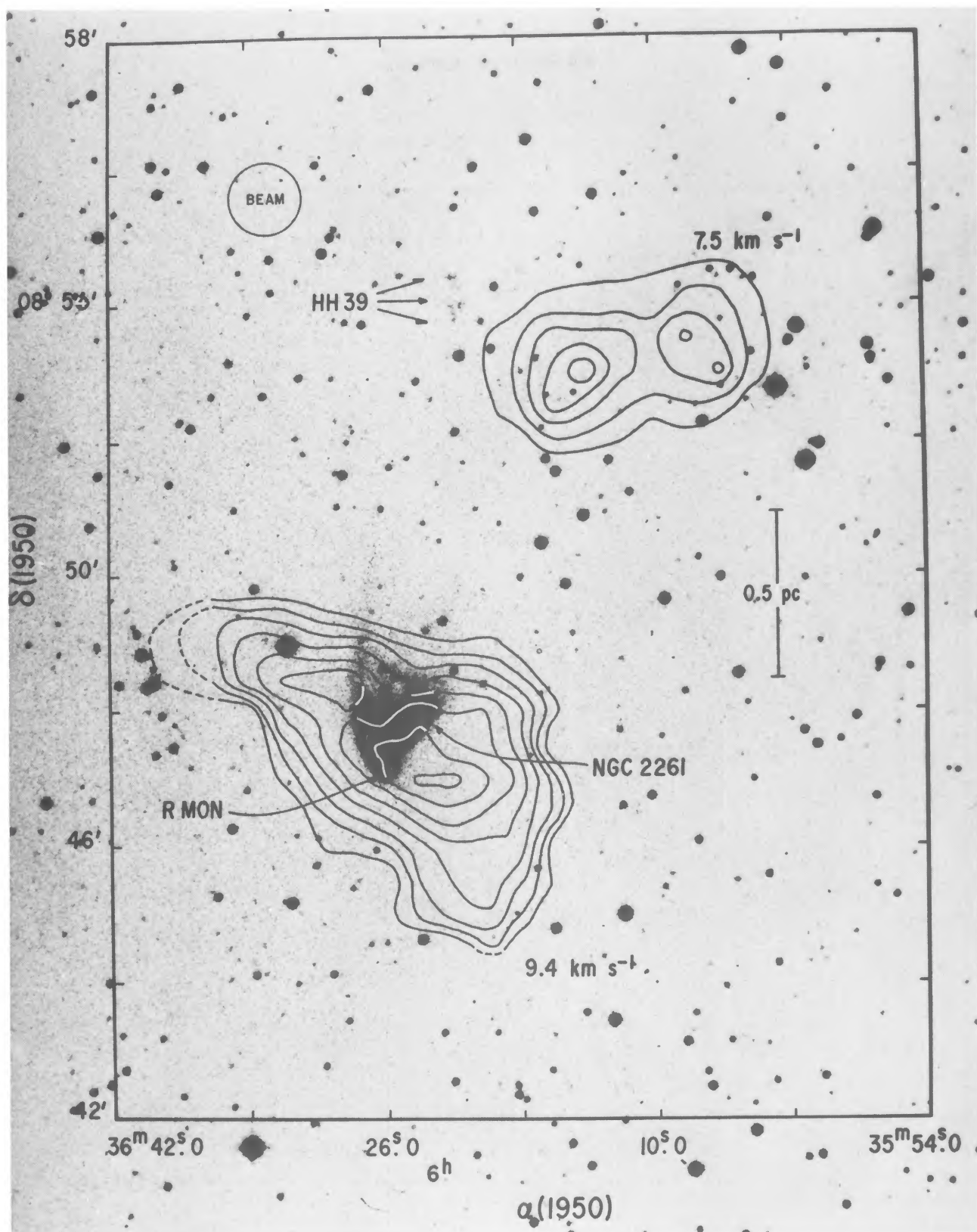


FIG. 2.— T_A contours at the estimated mean velocity of the R Mon cloud ($v_{\text{LSR}} = 9.4 \text{ km s}^{-1}$) and the HH 39 cloud ($v_{\text{LSR}} = 7.5 \text{ km s}^{-1}$). The lowest contour is $T_{\text{low}} = 2 \text{ K}$, and increments are $\Delta T = 1 \text{ K}$.

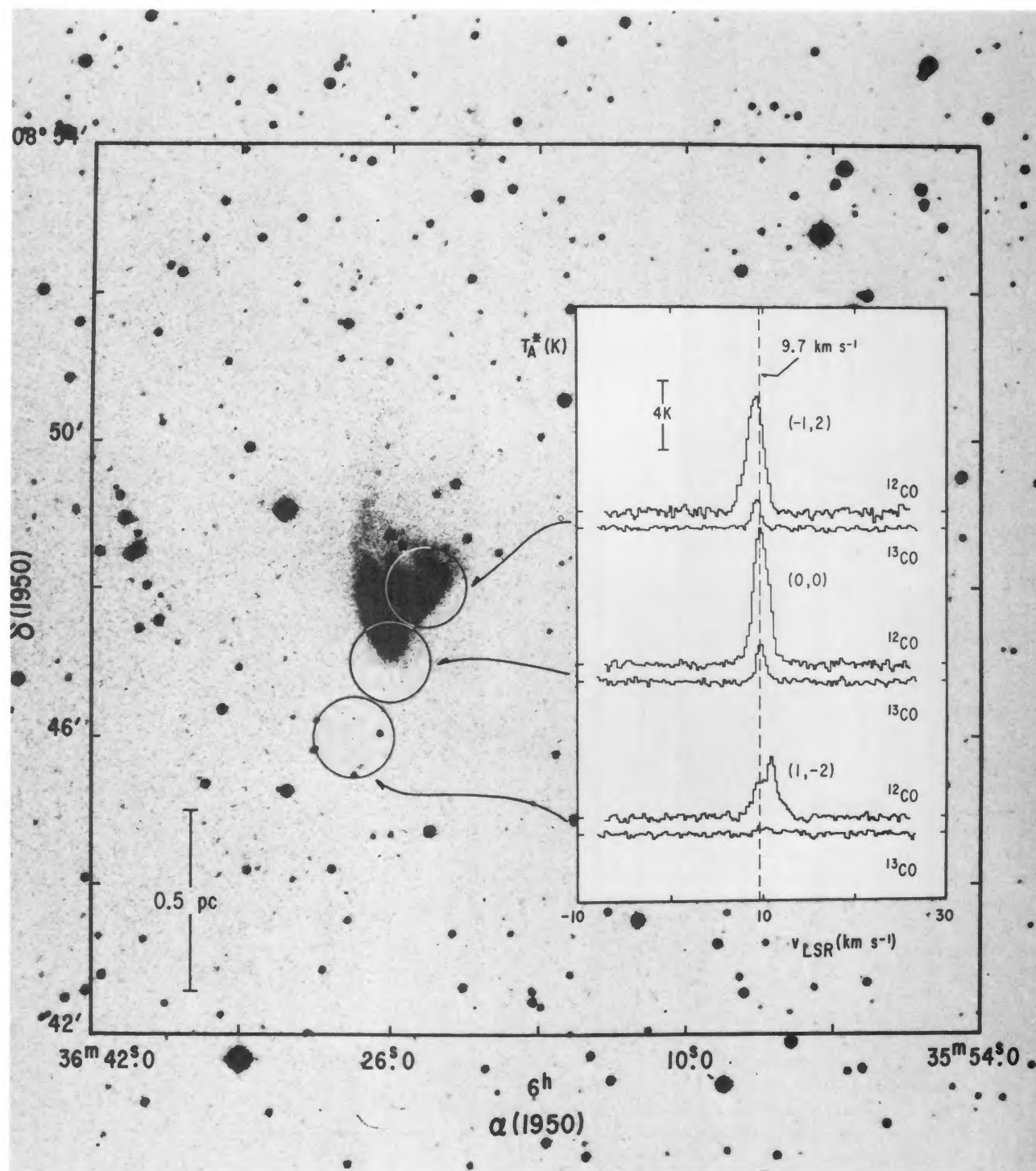


FIG. 3.— ^{12}CO and ^{13}CO spectra at three selected positions in the R Mon molecular cloud. Notice the presence of blueshifted and redshifted components in the spectra related to NGC 2261 and the obscured southern lobe, respectively.

about equal to the beam size, it is probably unresolved and observations at higher resolution may show it to be more pronounced. This suggests that NGC 2261 is actually part of a cavity in the molecular cloud. The walls of this cavity reflect the light of R Mon and give NGC 2261 its symmetrical shape.

The ^{12}CO map indicates an elongated shape for this molecular cloud. Two simple spatial configurations could possibly account for this; the cloud could be either prolate (cigar-shaped) or oblate (disk-shaped). Consideration of the optical appearance of NGC 2261 favors a disk-shaped cloud; if R Mon were placed at the center of a cigar-shaped cloud, its stellar wind would be expected to clear the central part of the cloud, breaking it into two separate pieces. In contrast, a disk-shaped cloud would confine the wind of R Mon in the direction of its plane, and cavities would be produced at the poles. Since the CO data favor a bipolar cavity, we will tentatively assume that this cloud is disk-shaped.

Inspection of the spectra obtained at different positions in this cloud reveals clear changes in the line shapes. Figure 3 shows the line profiles at three selected positions in this cloud: (0,0), (-1,2), and (1,-2). It can be seen from these spectra that there are two extra ^{12}CO components; one of them peaks to the north and is blueshifted with respect to the R Mon spectrum. The other peaks south and is redshifted with respect to the R Mon spectrum. In both cases the shift is of $\sim 2 \text{ km s}^{-1}$. These two extra components are more clearly displayed when contour maps at different velocities are made. Figure 4 shows maps at 7.7 and 11.1 km s^{-1} .

Material moving at 10.5 km s^{-1} (Fig. 5) is spatially distributed in a disk of considerable symmetry around R Mon, with its major axis also perpendicular to the axis of symmetry of NGC 2261. This higher symmetry is probably due to the fact that at this velocity the clump causing the optical indentation has no significant emission. In this sense this map gives a better representation of the actual shape of the disk. In this

map the bending of the isotherms at the optical position of the nebula is also evident, suggesting again a cavity in this region.

It is interesting to notice that, while the blueshifted molecular feature is well correlated with the optical nebula, the redshifted one possesses no optical counterpart. This suggests that the disk is not exactly edge-on, but tilted in such a way that the southern lobe is obscured to the observer by the disk. Thus our results confirm the bipolar nature of NGC 2261 already suggested by the faint nebulosity which can be seen in optical photographs opposite to NGC 2261 (Hubble 1916; Herbig 1960; Johnson 1966; Stockton, Chesley, and Chesley 1975).

To investigate column densities, we took high signal-to-noise ratio ^{13}CO spectra at selected positions in the cloud (see Fig. 1 and Table 1). We interpreted the CO data in the usual way (cf. Dickman 1978*b*). In Table 1 we present the parameters derived from these spectra.

From the derived column densities of ^{13}CO , N_{13} , and the relations given by Dickman (1978*b*), estimates of the total visual extinction, A_v , and molecular hydrogen column densities, N_{H_2} , can be obtained. We derived values of $A_v \approx 1-2$ mag for the center of the cloud. These values are probably too small, since a counting of stars following Dickman (1978*a*) suggests $A_v \approx 3$ mag. Discrepancies are expected, however, since the relations of Dickman (1978*b*) are only valid in a statistical sense and may differ from cloud to cloud. Therefore, based on the results of our star counting we will use, for this region, values for A_v and N_{H_2} a factor of 2 greater than those given by Dickman (1978*b*). That is,

$$\left(\frac{A_v}{\text{mag}}\right) = 8 \times 10^{-16} \left(\frac{N_{13}}{\text{cm}^{-2}}\right)$$

$$\left(\frac{N_{\text{H}_2}}{\text{cm}^{-2}}\right) = 1 \times 10^6 \left(\frac{N_{13}}{\text{cm}^{-2}}\right).$$

TABLE 1
PARAMETERS OF THE ^{12}CO AND ^{13}CO SPECTRA AT SELECTED POSITIONS

POSITION	^{12}CO			^{13}CO			$T_{\text{ex}}(\text{K})$	$N_{13}(\text{cm}^{-2})$	$A_v(\text{mag})$	$N_{\text{H}_2}(\text{cm}^{-2})$
	$T_L(\text{K})$	$\Delta v(\text{km s}^{-1})$	$v_{\text{LSR}}(\text{km s}^{-1})$	$T_L(\text{K})$	$\Delta v(\text{km s}^{-1})$	$v_{\text{LSR}}(\text{km s}^{-1})$				
(0,0)....	8.0	1.9	9.7	2.2	1.2	9.7	11.4	3.0×10^{15}	2.4	3.0×10^{21}
(0,-1)...	{ 4.6	1.2	10.8	$\lesssim 0.2$	...	...	...	...	...	...
	{ 5.0	1.4	9.4	1.5	1.6	9.7	...	...	...	...
(-2,0)...	9.5	1.8	9.7	2.6	1.1	9.5	12.9	3.5×10^{15}	2.8	3.5×10^{21}
(1,-2)...	{ 1.5	0.6	10.9	$\lesssim 0.2$	...	...	...	...	...	...
	{ 2.4	3.0	10.3	0.36	1.9	10.2	...	...	...	...
(-1,2)...	{ 0.8	0.6	7.2	0.2	...	...	...	...	...	...
	{ 6.9	2.0	9.1	1.7	1.1	9.2	...	...	...	...
(-6,12)...	3.6	1.4	7.5	0.4	0.9	7.4	6.8	3.4×10^{14}	0.27	3.4×10^{20}
(-2,14)...	0.4	3.4	8.6	$\lesssim 0.2$	...	...	...	...	...	...

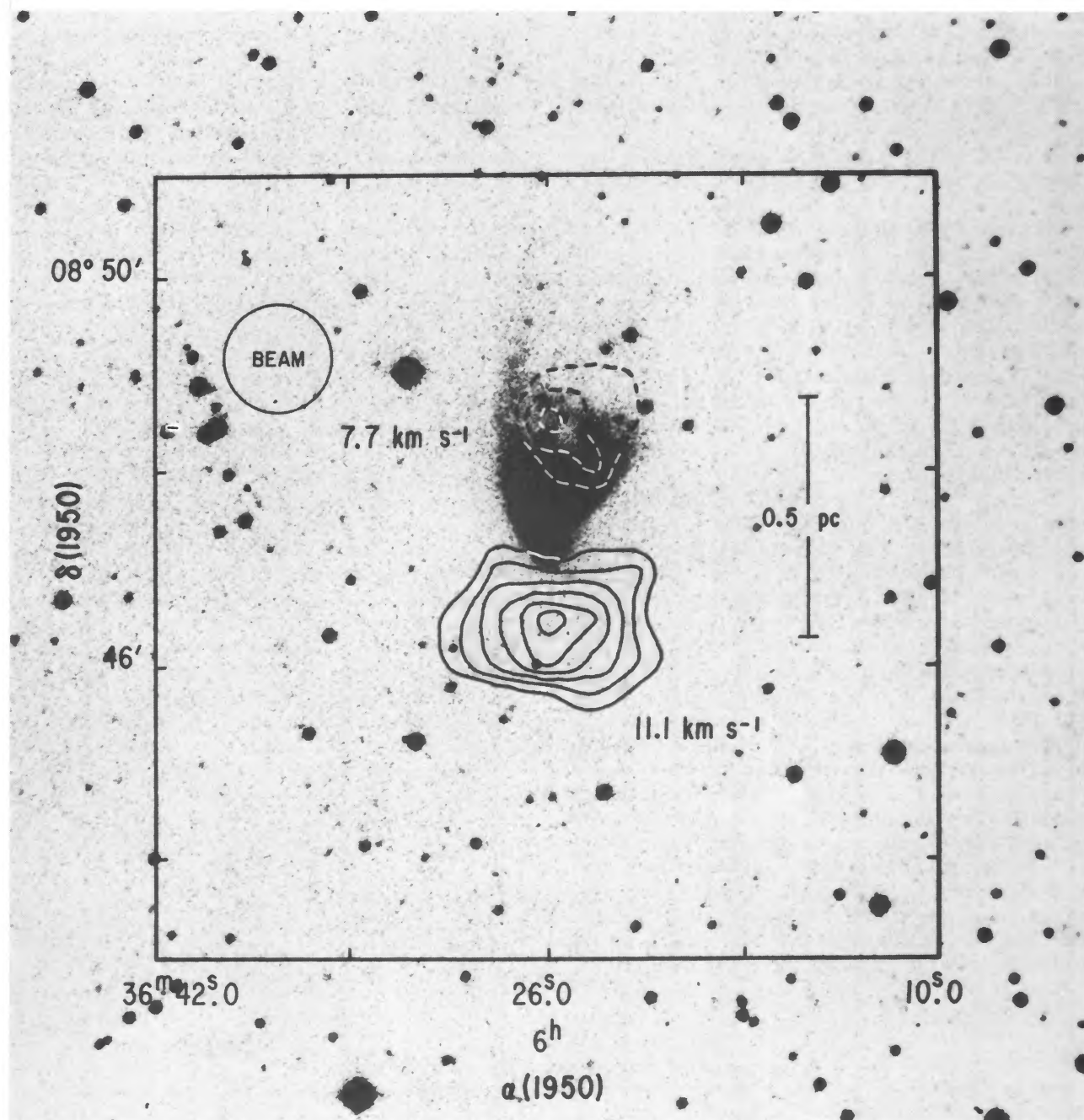


FIG. 4.— $T_{J=2-1}^*$ contour maps for the blueshifted and redshifted emission. $T_{\text{low}} = 2$ K and $\Delta T = 0.5$ K.

With these formulae and assuming that the cloud has dimensions of ~ 0.8 pc in diameter and ~ 0.4 pc in width, we derive a mean density of $n_{\text{H}_2} \approx 2000 \text{ cm}^{-3}$ for the cloud associated with R Mon. Multiplying by 1.4 to account for helium we derive for this cloud a mass of $\sim 30 M_{\odot}$. For these calculations a distance to R Mon of 690 pc was adopted (Johnson 1968).

As can be noticed from Table 1, the N_{13} value at R

Mon = (0,0) is lower than the N_{13} value at (-2,0). Although their difference is only about 15%, this can be taken as evidence of a cavity in the center of the disk. Indeed, since the signal-to-noise ratios of the ^{13}CO lines used are ~ 30 , we consider the 15% difference to be significant. We can therefore model the molecular cloud around R Mon as disk shaped with a cavity in its center (i.e., shaped like a doughnut). Similar models

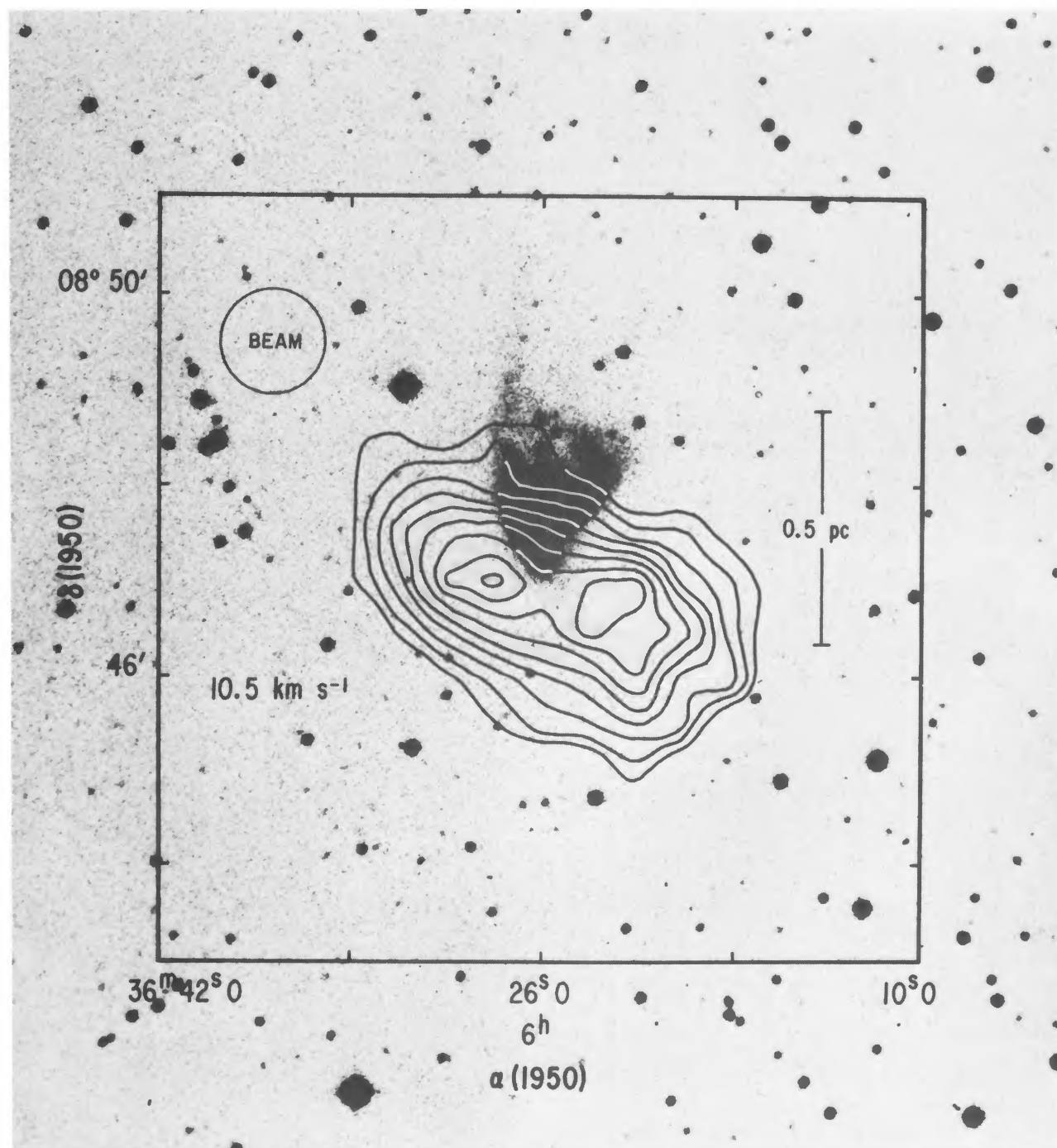


FIG. 5.— T_A^* contour map for $v_{\text{LSR}} = 10.5 \text{ km s}^{-1}$. $T_{\text{low}} = 2 \text{ K}$ and $\Delta T = 0.5 \text{ K}$.

have been proposed for other bipolar and cometary nebulae by Cohen (1974), Herbig (1975), and Schmidt, Angel, and Beaver (1978).

On the other hand, we also find that the excitation temperature, T_{ex} , derived from the ^{12}CO is lower at the position of R Mon than at the position $(-2, 0)$. This result can be interpreted in terms of the doughnut-shaped cloud if its inner parts are hotter than the outer

ones. That is, given the doughnut shape, a line of sight passing through its inner edge samples, on the average, hotter material than a line of sight passing through the center. It is important to mention here that although the large optical depths derived for the ^{12}CO would imply that we are only observing the periphery of the cloud, it is well known that the ^{12}CO observations actually sample material deep in the cloud. The reason

for this is not yet clearly known. It is probably a consequence of macroturbulence (Baker 1976), or large-scale motions within the cloud (Goldreich and Kwan 1974; Plambeck, Williams, and Goldsmith 1977). We are then justified in assuming that the derived T_{ex} values are some sort of mean value along the line of sight. However, we now face a question: What is causing the hotter inner region? One possibility is that the stellar radiation from R Mon is heating the dust in the inner part of the disk. Energy transfer from the hot dust to the gas could be expected to account for the observed temperature. Before considering the possibility of stellar heating we note that cosmic rays will provide heating throughout the cloud. For $n_{\text{H}_2} \approx 2000 \text{ cm}^{-3}$ the cosmic rays will provide a heating rate of $\Gamma_{\text{cr}} \approx 1.3 \times 10^{-24} \text{ ergs cm}^{-3} \text{ s}^{-1}$ and they alone will heat the gas to a temperature $T_g \approx 8 \text{ K}$ (Goldsmith and Langer 1978). This is $\sim 4 \text{ K}$ less than the observed gas temperature. Now we consider the stellar contribution (from R Mon) to gas heating.

The stellar radiation will heat the dust to a temperature given by (Loren and Wootten 1978):

$$\left(\frac{T_d}{\text{K}}\right) \approx 22.9 \left[\frac{L_{\lambda > 912 \text{ Å}}}{10^{38} \text{ ergs s}^{-1}} \left(\frac{d}{\text{pc}}\right)^{-2} \right]^{0.2}.$$

For the inner regions of the molecular cloud we adopt $d \approx 0.1 \text{ pc}$ and for R Mon, $L_{\lambda > 912 \text{ Å}} \approx 660 L_{\odot}$. This gives $T_d \approx 28 \text{ K}$. However, transfer of energy from dust to gas is rather inefficient. This rate of transfer is given (Leung 1975; Goldsmith and Langer 1978) as,

$$\Gamma_{dg} = 2.4 \times 10^{-33} T_g^{1/2} (T_d - T_g) n_{\text{H}_2}^2.$$

For the values previously obtained we find $\Gamma_{dg} = 1.4 \times 10^{-25} \text{ ergs cm}^{-3} \text{ s}^{-1}$; about an order of magnitude less than the heating due to cosmic rays. Clearly, neither stellar radiation nor cosmic rays appear to be able to heat the gas to the observed temperature. This apparent lack of a heating mechanism has been found also for several bright-rimmed clouds (Lada and Black 1976; Elmegreen, Dickinson, and Lada 1978). These last authors have proposed that for recently compressed gas such as that of bright-rimmed clouds, an important heat source is the relaxation of internal magnetic fields. The inner parts of the cloud associated with R Mon have probably been recently compressed by the stellar wind of R Mon and the relaxation mechanism proposed by Elmegreen, Dickinson, and Lada (1978) could be important.

b) The Molecular Cloud Associated with Herbig-Haro Object 39

Another molecular cloud was detected west of HH 39. It has a shape and angular size similar to those of the cloud associated with R Mon. However, the ^{12}CO

and ^{13}CO observations (Table 1) show that the T_{ex} and N_{13} are lower in the HH 39 cloud. Assuming similar dimensions for both clouds we derive a mean density of $n_{\text{H}_2} \approx 200 \text{ cm}^{-3}$ and a mass $\sim 3 M_{\odot}$ for this cloud.

It is interesting to note that both clouds show two maxima placed symmetrically with respect to the center. This fact suggests that the HH 39 cloud also may be shaped like a doughnut. For the R Mon cloud, we interpret the inner cavity as created by a strong stellar wind from R Mon. Close examination of the Palomar plates reveals an extremely faint star at the center of the HH 39 cloud. Therefore, it can be argued that this faint object corresponds to a star which is also creating a cavity around it, possibly via a stellar wind. However, the low total mass of this cloud ($\sim 3 M_{\odot}$) appears to preclude the formation of a luminous star. Also, there is no evidence of reflected light in this cloud and this suggests that the star could be just a foreground or background object. We conclude that there is no satisfactory explanation for the similarity in the shape of the two observed clouds.

Another interesting relation between the R Mon and HH 39 clouds is that they show a similar alignment. Besides the possibility of a coincidence, several mechanisms could be responsible for this. For instance, if both clouds formed from a larger cloud having angular momentum, the subsequent collapse of each cloud will occur faster parallel to the common axis of rotation. However, within observational error ($\sim 0.2 \text{ km s}^{-1}$) our CO observations do not show systematic velocity gradients evidencing rotation in either of the clouds. Also, the differential gravitational z -field of the Galaxy could also provide an alignment mechanism. However, the clouds observed have their major axis near perpendicular to the galactic plane, while the differential z -field is expected to align clouds with their major axis parallel to the galactic plane (Disney and Hopper 1975). An alternative possibility is that both clouds have collapsed faster along the lines of the galactic magnetic field (Mouschovias 1976*a, b*). Indeed, the axes of symmetry of the clouds are approximately parallel to the plane of the Galaxy. If the galactic magnetic field is parallel to the plane of the Galaxy, the common alignment of these clouds may be caused by such a magnetic field. Also, the large polarization observed in NGC 2261 (Hall 1965; Zellner 1970) suggests aligned dust grains with their major axis perpendicular to the nebula axis. A magnetic field could be the aligning agent, such as proposed by Schmidt, Angel, and Beaver (1978) for the bipolar nebulae CRL 2688 and MI-92.

c) The Relationship between R Mon, NGC 2261, and HH 39: The Interstellar Nozzle

The presence of these three optical objects and of the two-molecular clouds described previously suggests a consistent scenario for the region. R Mon is a star

recently formed out of the disk-shaped molecular cloud associated with it. Since R Mon is at the center of the cloud, an *in situ* formation is favored and the hypothesis that R Mon could be an interloper (Arny and Bechis 1978) is unlikely. It is known that R Mon has a stellar wind with a terminal velocity of around 200 km s⁻¹. This can be inferred from the optical results of Stockton, Chesley, and Chesley (1975). This stellar wind has pushed out the material that originally existed around R Mon and has created a bipolar cavity in the disk. Cantó (1980), Cantó and Rodríguez (1980), and Barral and Cantó (1980) have explored in detail the characteristics of these cavities. They conclude that a very important consequence of a disk-like pressure distribution around the star is that the stellar wind, initially isotropic, can be channeled into two antiparallel annular streams. Under certain conditions these streams are eventually forced to narrow and shock against themselves far from the star. Cantó and Rodríguez (1980) proposed this "focusing" mechanism as an explanation for Herbig-Haro objects.

As shown by Cantó and Rodríguez (1980), this "nozzle" effect is able to overcome in a natural way the most intriguing characteristic of Herbig-Haro objects: the lack of an energy source within or very near the object itself. While no stellar or protostellar objects have been detected at the position of the HH-objects, infrared (Strom, Grasdalen, and Strom 1974) and radio (Rodríguez *et al.* 1978; 1980; Haschick *et al.* 1980) results often reveal heavily obscured young stars in the vicinity of HH-objects. Since these stars are expected to have strong stellar winds and since HH-objects are most likely shocked gas in the process of cooling (Raymond 1976, 1979; Dopita 1978) most recent models try to explain HH-objects as the result of the interaction between a stellar wind and the surrounding molecular cloud (Schwartz 1975, 1978; Rodríguez *et al.* 1980; Haschick *et al.* 1980; Cantó 1978, 1980). A problem, however, is faced by the models. This is that HH-objects usually subtend small solid angles with respect to the proposed exciting star. If an isotropic wind is taken, unrealistic values for the mechanical wind energy are required. This difficulty disappears in the focusing mechanism proposed by Cantó and Rodríguez (1980). Around R Mon we are finding evidence for this process. There, the annular bipolar streams created by the wind of R Mon upon interaction with its disk-shaped cloud are injected into the low-density surroundings. Since the ram pressure of the wind acting on the inner side of the stream is rapidly decreasing while the external pressure is likely to remain constant, the streams must narrow (see Cantó 1980 for details). This process is probably occurring closer to the star than expected, due to the presence of the northern molecular cloud. This cloud is refracting the western side of the annular stream, making it to

shock against the eastern side and creating HH 39. Figure 6 shows an artist's depiction of this scenario.

Finally, let us estimate some of the parameters of the wind of R Mon.

Let $\dot{M}_*$ and V_* be the mass-loss rate and terminal velocity of the wind. If P is the gas pressure at the disk center, the pressure balance condition is expressed by

$$\frac{\dot{M}_* V_*}{4\pi R_0^2} = P, \quad (1)$$

where R_0 is the radius of the cavity formed by the wind at the disk's center. In order to calculate P we must consider turbulent motions, since they are probably the dominant pressure component. This follows from the widths of the lines, which are much wider than expected for thermal motions alone. Therefore,

$$P \approx \rho v_{\text{tur}}^2, \quad (2)$$

where ρ is the mass density at the disk center and v_{tur} the mean turbulent velocity; v_{tur} can be obtained from the full width at half-power Δv_{13} by

$$v_{\text{tur}} = \Delta v_{13} / (8 \ln 2)^{1/2}, \quad (3)$$

and ρ is related to the molecular hydrogen number density by

$$\rho = 2 m_{\text{H}} n_{\text{H}_2}, \quad (4)$$

where m_{H} is the mass of a hydrogen atom.

Substituting equations (2)–(4) into (1) and expressing it in convenient units, we find

$$\left(\frac{\dot{M}_*}{10^{-7} M_{\odot} \text{ yr}^{-1}} \right) \left(\frac{V_*}{100 \text{ km s}^{-1}} \right) = 2.66 \times 10^{-2} \left(\frac{R_0}{\text{pc}} \right)^2 \left(\frac{\Delta v_{13}}{\text{km s}^{-1}} \right)^2 n_{\text{H}_2}. \quad (5)$$

From Table 1 and the results above, appropriate values for R_0 , n_{H_2} , and Δv_{13} are 0.06 pc, 2000 cm⁻³, and 1.2 km s⁻¹, respectively. Therefore, for R Mon

$$\left(\frac{\dot{M}_*}{10^{-7} M_{\odot} \text{ yr}^{-1}} \right) \left(\frac{V_*}{100 \text{ km s}^{-1}} \right) \approx 0.28,$$

which is of the order of the values we expect for a T Tauri-like star (Kuhi 1964). Notice, however, that this value is a lower limit since we have not considered magnetic pressure in equation (2).

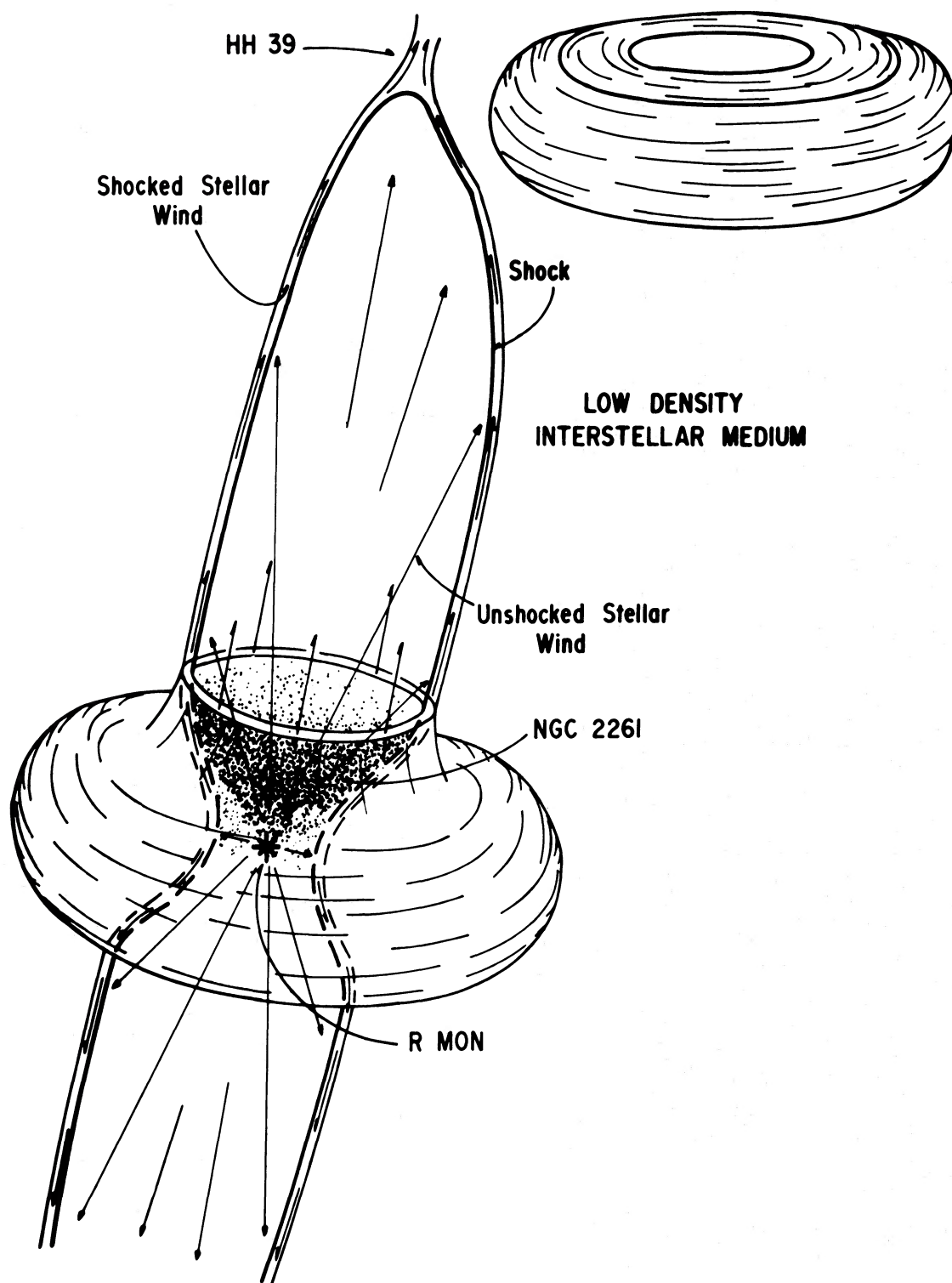


FIG. 6.—A depiction of the model of the interstellar nozzle. The interaction of the stellar wind of R Mon with the surrounding disk-shaped cloud has created a bipolar cavity that focuses the wind into two antiparallel annular streams. Outside of the cloud the counterpressure is provided by the low-density interstellar medium. The presence of another cloud makes the northern stream to shock against itself. HH 39 is formed as a result of this shock.

If we adopt a wind velocity of $\sim 200 \text{ km s}^{-1}$ as suggested by the optical observations of Stockton, Chesley, and Chesley (1975), we get

$$\dot{M}_* \sim 1.4 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$$

as an estimate of the mass-loss rate of R Mon.

III. THE PHENOMENON OF BIPOLAR MASS OUTFLOW: CIRCUMSTELLAR OR INTERSTELLAR DISKS?

If a recently formed star has a stellar wind and is located in a disk-shaped molecular environment, the wind will be channeled into two opposite streams. For R Mon this channeling is being made by the disk-shaped molecular cloud discussed previously. It appears convenient to refer to these kind of clouds as "interstellar" disks since their dimensions (tenths of a pc) are much larger than those of a "circumstellar" disk (thousandths of a pc). In the region studied here, the relatively low extinction allows the detection and analysis of optical objects (R Mon, NGC 2261, and HH 39), in addition to radio objects (the two molecular clouds). This permits a better understanding of the various phenomena taking place. Recently, other examples of bipolar or anisotropic mass outflows have been observed in heavily obscured regions of star formation. The cases known to us are those of L1551 (Snell, Loren, and Plambeck 1980), Cep A (Rodríguez, Ho, and Moran 1980), GL 490 (Lada and Harvey 1980), and GGD 12-15 and GGD 27-28 (Rodríguez *et al.* 1981). The velocities involved in these bipolar outflows ($10\text{--}50 \text{ km s}^{-1}$) are larger than the values observed for R Mon ($\sim a \text{ few km s}^{-1}$). This suggests that in the several cases mentioned there are more powerful winds involved. This suggestion is supported by the fact that the other cases observed occur in larger clouds. These clouds are capable of forming more massive stars and of providing the large extinctions that difficult the detection of optical objects. The other examples of bipolar mass outflow are also known to be associated with more luminous objects from the presence of H_2O masers and ultracompact H II regions (Rodríguez *et al.* 1980; Lada and Harvey 1980). For L1551 Snell, Loren, and Plambeck (1980) have proposed that a circumstellar disk is responsible for the observed bipolar outflow. Our results indicate that for R Mon it is a much larger interstellar disk that is channeling the outflow. Unfortunately,

it is difficult to test if in the more complex clouds we also have interstellar disks since there are problems of lack of contrast in the ^{12}CO .

Finally, we also want to remark that since the disk-shaped cloud around the wind-producing star provides a natural channeling environment for the wind, there is no need for an anisotropy in the wind itself in order to produce the observed bipolar outflows.

IV. CONCLUSIONS

The results of our carbon monoxide observations of the region containing R Mon, NGC 2261, and HH 39 can be summarized as follows.

1) R Mon lies at the center of a disk-shaped molecular cloud. The stellar wind of R Mon has created a bipolar cavity in the cloud. Due to the tilt in the molecular disk only the northern lobe (NGC 2261) is easily observed in the visible. The presence of blueshifted and redshifted components in the ^{12}CO indicate the existence of an obscured southern lobe. Thus, NGC 2261 is not a cometary nebula but one of the lobes of a bipolar nebula.

2) The bipolar cavity channels the wind of R Mon into two antiparallel streams. The northern stream interacts with another molecular cloud at $\sim 1.4 \text{ pc}$ from R Mon. As a result of this interaction a shock occurs in the stream and HH 39 is formed.

3) The available radio and optical data allow a determination of the mass-loss rate for R Mon. For a wind terminal velocity of 200 km s^{-1} we obtain $\dot{M}_* \approx 1.4 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$.

4) It is probable that a considerable fraction of the young stars are formed in disk-shaped molecular environments. We could refer to these clouds as "interstellar" disks since their dimensions (tenths of a pc) are much larger than those of the "circumstellar" disks (thousandths of a pc). Circumstellar disks have been proposed to explain the anisotropic mass outflows observed in some regions of star formation. Our results suggest that a much larger interstellar disk could also explain the phenomenon.

We are thankful to A. García for his help in the preparation of the graphical material. L. F. R. acknowledges partial support from CONACYT, México.

REFERENCES

- Arny, T. T., and Bechis, K. P. 1978, *Ap. J.*, **226**, 455.
 ———. 1980, preprint.
 Baker, P. L. 1976, *Astr. Ap.*, **50**, 327.
 Barral, J. F., and Cantó, J. 1980, *Rev. Mexicana Astr. Ap.*, **5**, in press.
 Cantó, J. 1978, *Astr. Ap.*, **70**, 111.
 ———. 1980, *Astr. Ap.*, **86**, 327.
 Cantó, J., and Rodríguez, L. F. 1980, *Ap. J.*, **239**, 982.
 Cohen, M. 1974, *Pub. A.S.P.*, **86**, 813.
 Dickman, R. L. 1978a, *A. J.*, **83**, 363.
 ———. 1978b, *Ap. J. Suppl.*, **37**, 407.
 Disney, M. J., and Hopper, P. B. 1975, *M.N.R.A.S.*, **170**, 177.
 Dopita, M. A. 1978, *Ap. J. Suppl.*, **37**, 117.
 Duncan, J. C. 1956, *Pub. A.S.P.*, **68**, 517.
 Elmegreen, B. G., Dickinson, D. F., and Lada, C. J. 1978, *Ap. J.*, **220**, 853.
 Goldreich, P., and Kwan, J. 1974, *Ap. J.*, **189**, 441.
 Goldsmith, P. F., and Langer, W. D. 1978, *Ap. J.*, **222**, 881.
 Hall, R. C. 1965, *Pub. A.S.P.*, **77**, 158.
 Haschick, A. D., Moran, J. M., Rodríguez, L. F., Burke, B. F., Greenfield, P., and García-Barreto, J. A. 1980, *Ap. J.*, **237**, 26.
 Herbig, G. H. 1960, *Ap. J. Suppl.*, **4**, 337.

- . 1968, *Ap. J.*, **152**, 439.
 ———. 1975, *Ap. J.*, **200**, 1.
 Herbig, G. H., and Rao, N. K. 1972, *Ap. J.*, **174**, 401.
 Hubble, E. P. 1916, *Ap. J.*, **44**, 190.
 Imhoff, C. L., and Mendoza, V. E. E. 1974, *Rev. Mexicana Astr. Ap.*, **1**, 25.
 Johnson, H. M. 1966, *A. J.*, **71**, 224.
 Johnson, H. L. 1968, in *Nebulae and Interstellar Matter*, ed. L. H. Aller and B. M. Middlehurst (Chicago: University of Chicago Press), p. 167.
 Joy, A. H. 1945, *Ap. J.*, **102**, 168.
 Kuhi, L. V. 1964, *Ap. J.*, **140**, 1409.
 Lada, C. J., and Black, J. H. 1976, *Ap. J. (Letters)*, **203**, L75.
 Lada, C. J., and Harvey, P. M. 1980, preprint.
 Lampland, C. O. 1926, *Pop. Astr.*, **34**, 621 (*Pub. A.S.P.*, **5**, 390).
 ———. 1931, *Pub. A.S.P.*, **43**, 296.
 Leung, C. M., 1975, *Ap. J.*, **199**, 340.
 Loren, R. B., and Vanden Bout, P. A., and Davis, J. H. 1973, *Ap. J. (Letters)*, **185**, L67.
 Loren, R. B., and Wootten, H. A. 1978, *Ap. J. (Letters)*, **225**, L81.
 Meaburn, J. 1978, *Appl. Optics*, **17**, 127.
 Mendoza, V. E. E. 1966, *Ap. J.*, **143**, 1010.
 ———. 1970, *Mem. Soc. Roy. Sci. de Liege*, **19**, 319 (Series V).
 Mouschovias, T. Ch. 1976a, *Ap. J.*, **206**, 753.
 ———. 1976b, *Ap. J.*, **207**, 141.
 Plambeck, R. L., Williams, D. R., and Goldsmith, P. F. 1977, *Ap. J. (Letters)*, **213**, L41.
 Raymond, J. C. 1976, Ph.D. thesis, University of Wisconsin, Madison.
 ———. 1979, *Ap. J. Suppl.*, **39**, 1.
 Rodríguez, L. F., Moran, J. M., Dickinson, D. F., and Gyulbudaghian, A. L. 1978, *Ap. J.*, **226**, 115.
 Rodríguez, L. F., Moran, J. M., Ho, P. T. P., and Gottlieb, E. W. 1980, *Ap. J.*, **235**, 845.
 Rodríguez, L. F., Carral, P., Ho, P. T. P., and Moran, J. M. 1981, in preparation.
 Rodríguez, L. F., Ho, P. T. P., and Moran, J. M. 1980, *Ap. J. (Letters)*, **240**, L149.
 Schmidt, G. D., Angel, J. R. P., and Beaver, E. A. 1978, *Ap. J.*, **219**, 477.
 Schmidt, J. F. J. 1861, *Astr. Nach.*, **55**, 91.
 Schwartz, R. D. 1975, *Ap. J.*, **195**, 631.
 ———. 1978, *Ap. J.*, **223**, 884.
 Slipher, V. M. 1912, *Lowell Obs. Bull.*, No. 2.
 Snell, R. L., Loren, R. B., and Plambeck, R. L. 1980, *Ap. J. (Letters)*, **239**, L17.
 Stockton, A., Chesley, D., and Chesley, S. 1975, *Ap. J.*, **199**, 406.
 Strom, S. E., Grasdalen, G. L., and Strom, K. M. 1974, *Ap. J.*, **191**, 111.
 Ulich, B. L., and Haas, R. W. 1976, *Ap. J. Suppl.*, **30**, 247.
 Wilson, W. J., Schwartz, P. R., and Epstein, E. E. 1973, *Ap. J.*, **183**, 871.
 Zellner, B. 1970, *A. J.*, **75**, 182.

J. F. BARRAL, J. CANTÓ, P. CARRAL, and L. F. RODRÍGUEZ: Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 70-264, México, D.F., México