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CO OBSERVATIONS OF A HIGH-LATITUDE MOLECULAR CLOUD ASSOCIATED WITH NGC 7023

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ABSTRACT

We present a ^{12}CO map of a molecular cloud associated with NGC 7023. Measurements of ^{13}CO and CS were made to obtain column densities and densities. Optical evidence for recent star formation in this cloud is supported by our detection of a ^{12}CO peak at the position of a weak 6 cm continuum source. No optical counterpart is present. The ^{12}CO line widths and line-center velocities suggest, furthermore, that an additional velocity feature is in this same area of the cloud.

NGC 7023 is unusual because it lies at a high galactic latitude of $\sim 14°$. The cloud is also slightly elongated, with an orientation similar to that of the galactic magnetic field, as inferred from published polarization maps. This orientation is at an angle of some 50° from the normal to the galactic plane. We briefly discuss the possibility that the cloud's elongation is due to the flow of matter along magnetic field lines.

Subject headings: interstellar: molecules — nebulae: individual — stars: formation

I. INTRODUCTION

NGC 7023 is a reflection nebula which is located about 14° above the galactic plane, in a region devoid of other nebulosity within roughly a 5° radius. The source of illumination for NGC 7023 is HD 200775, a B3e (III or IV) star (Mendoza 1958) located at a distance of 440 pc from the Sun (Viotti 1969). This star is the center of a T association (Weston 1953) consisting of some 14 stars showing variability and Hα emission. Included in the group are LkHα 275, 276, and 427 (Herbig 1962; Herbig and Rao 1972). At least three of the T Tauri stars appear to be members of binary systems (Romano 1975). The total stellar mass in the central cluster has been estimated to be about 100 $M_\odot$ by Aveni and Hunter (1969).

The presence of a Herbig Be star, Hα emitters, irregular variables, and T Tauri stars makes NGC 7023 an excellent candidate for the study of low-mass star formation. HD 200775 itself is classified as a pre–main-sequence star by Strom, Strom, and Yost (1972). They searched for further evidence of protostellar activity by photographing the central 75 square arcmin region around HD 200775 at 1 μm; they found a number of probable embedded stars. A weak detection (greater than or equal to 0.2 K) of OH was made near HD 200775 at 1667 MHz by Lépine and Nguyen-Quang-Rieu (1975), and is possibly associated with the star itself. There was an indication of both a narrow and a wide (greater than or equal to 20 km s^{-1}) component at this frequency. A weak 6 cm source (0.12 $\pm$ 0.04 Jy peak) has also been detected in the region with the radio telescope at Bonn (Pankonin and Walmsley 1977).

Carbon monoxide was first reported in NGC 7023 by Loren, Vanden Bout, and Davis (1973) in a survey of Herbig Ae and Be stars. They detected a ^{12}CO temperature of 12.8 K at the position of HD 200775, i.e., at $\alpha(1950.0) = 21^h00^m59^s.7$, $\delta(1950.0) = 67°57'55''.5$. In the present investigation we have mapped the cloud in ^{12}CO out to a 6 K temperature contour level, covering a $\frac{1}{2}° \times 1°$ area. We have also sampled the region in ^{13}CO and CS in order to estimate column densities and space densities.

II. OBSERVATIONS AND RESULTS

a) ^{12}CO *Observations*

We observed NGC 7023 using the 16 foot (5 m) radio telescope of the Millimeter Wave Observatory in Fort Davis, Texas,[1] in 1977 February. The $J = 1 \rightarrow 0$ (2.7 mm) transition of ^{12}CO was mapped with nearly single-beam spacing of 3′ (half-power beamwidth [HPBW] = 2′.7 at 115 GHz) over the area $\alpha = 21^h03^m$–20^h59^m, $\delta = 67°10'$–$68°15'$. Double-beam spacing was used in much of the southern region of the molecular cloud, where temperatures were rather uniform. Half-beam spacings were applied to the central 15′ × 10′ area, which included steeper temperature gradients. The filter bank of 40 channels, each 250 kHz wide, provided a velocity resolution of 0.65 km s^{-1} for ^{12}CO. Integration times of 5 minutes for ^{12}CO and 15 minutes for ^{13}CO, with chopping between

[1] The Millimeter Wave Observatory is operated by the Electrical Engineering Research Laboratory, University of Texas at Austin, with support from the National Aeronautics and Space Administration, the National Science Foundation, and McDonald Observatory. The instrumentation used for spectral-line observations with this antenna was developed jointly by the University of Texas, Bell Telephone Laboratories, and the Radio Astronomy Division of the Center for Astrophysics.

signal and comparison frequencies, allowed detection down to a level of 1–2 K.

The antenna temperatures were corrected for elevation by using the calibration of Davis and Vanden Bout (1973). Contours of these corrected, equivalent Rayleigh-Jeans temperatures derived from ^{12}CO measurements are superposed on the red plate of NGC 7023 from the Palomar Observatory Sky Survey in Figure 1. The dotted lines indicate regions in which double-beam spacing was used.

The outer radio contours follow the optical outline of a conspicuous dark cloud which is evident from the paucity of stars relative to the adjacent regions. The contours are very uniform over most of the cloud, showing temperatures of 6–9 K.

A hole in the northwestern part of the cloud near $\alpha = 21^h00^m$, $\delta = 67°58'$ apparent in the photograph of Figure 1 is due to increased star counts within the bounds of the tick-marked region. This region was noted by Weston (1953), whose studies indicated that the apparent clustering of stars there had no common proper motion and must be an optical grouping caused by a window in the cloud. In the hole the ^{12}CO corrected temperatures drop to 6–7 K, as compared with the 11–14 K measurements around the periphery. The ^{12}CO temperatures here could be due to emission from the edge of the hole because of poor angular resolution rather than to the presence of CO in the optical hole itself.

The peak temperatures of 14–15 K occur in two regions, south and east of the central star. One hot spot is at $\alpha = 21^h00^m$, $\delta = 67°52'$. The second is at $\alpha = 21^h02^m$, $\delta = 67°58'$, which is at the position of the 6 cm source previously mentioned.

The measurements of the line centers with respect to the local standard of rest (LSR) for the ^{12}CO observations yield an average LSR velocity throughout the entire cloud of $\langle v_{LSR} \rangle_{cld} = 2.7 \pm 0.4$ km s^{-1}. There is no apparent velocity gradient in any direction. There is, however, a tendency for the line-center velocities in the area $\alpha = 21^h01^m.75$–$21^h02^m.25$, $\delta = 67°52'$–$67°58'$ (hereafter Region A) to be redshifted to velocities 0.5 km s^{-1} larger than the average velocity in the cloud; that is, in Region A, $\langle v_{LSR} \rangle_A = 3.2 \pm 0.3$ km s^{-1}. This region is roughly the northeastern part of the cloud within the large 10 K contour of Figure 1. At the location of the embedded 6 cm source (which is contained within Region A) the v_{LSR} is redshifted by 1 km s^{-1} with respect to the average line-center velocity of the entire cloud.

For comparison, we consider the region $\alpha = 20^h59^m$–$21^h00^m.5$, $\delta = 67°52'$–$67°58'$ (hereafter Region B), which is roughly the northwestern part of the cloud within the large 10 K boundary. Here, $\langle v_{LSR} \rangle_B = 2.8 \pm 0.3$ km s^{-1}, essentially the same value as that for the entire cloud. Finally, we consider the southern part of the cloud (hereafter Region C), south of $\delta = 67°40'$. Here, $\langle v_{LSR} \rangle_C = 2.7 \pm 0.4$ km s^{-1}, again the same as that for the entire cloud.

The average full width at half-maximum (FWHM) for the ^{12}CO line profiles, Δv, was also measured over the cloud as a whole and over the individual regions A, B, and C for comparison. For the entire cloud, $\langle \Delta v \rangle_{cld} = 2.4 \pm 0.7$ km s^{-1}. In Region B, $\langle \Delta v \rangle_B = 2.3 \pm 0.6$ km s^{-1}; in Region C, $\langle \Delta v \rangle_C = 2.1 \pm 0.6$ km s^{-1}. As was the case for the average line-center velocities, the average FWHM values in regions B and C are comparable to that for the cloud as a whole. In Region A, however, we find that $\langle \Delta v \rangle_A$ is larger, 3.2 ± 0.7 km s^{-1}.

The combination of the ^{12}CO velocity and line-width data suggests that Region A contains an unresolved velocity feature. This could be a result of some activity in the cloud that is related to the source of the 6 cm emission.

b) ^{13}CO *Observations and Column Densities*

Several measurements of ^{13}CO were made in the central region, as well as at one point in the southern extension of the cloud. The FWHM for these lines, along with the temperatures T for ^{13}CO and ^{12}CO, may be combined to obtain the column densities at these points by using the formula

$$N(^{13}\mathrm{CO}) = \frac{2.31 \times 10^{14} \tau(^{13}\mathrm{CO}) \Delta v(^{13}\mathrm{CO})(T_{ex} + 0.91)}{1 - \exp(-5.29/T_{ex})} ,$$

where $\tau(^{13}\mathrm{CO}) = -\ln [1 - T(^{13}\mathrm{CO})/T(^{12}\mathrm{CO})]$ is the optical depth for ^{13}CO and

$$T_{ex} = 5.54 \left\{ \ln \left[1 + \frac{5.54}{T(^{12}\mathrm{CO}) + 0.817} \right] \right\}^{-1}$$

is the excitation temperature for ^{12}CO. This formula makes use of the assumption that the ^{12}CO lines are optically thick and that the ^{13}CO excitation temperature is the same as the ^{12}CO excitation temperature. Also, the antenna beamwidth is assumed to be smaller than the source, and the effective beam efficiency is taken to be unity.

Results are presented in Table 1. The ^{13}CO column densities range between 4.4 and 17.2×10^{15} cm^{-2}, with the exception of an upper limit of 1.2×10^{15} cm^{-2} at one point.

c) CS *Observations*

We searched for the $J = 3 \rightarrow 2$ (147 GHz) transition of CS at three of the points in the central area where ^{13}CO was observed. A positive detection greater than 0.5 K was observed only at the position of the 6 cm continuum source; the CS temperature there was 1.3 ± 0.7 K and the velocity was 3.2 km s^{-1}. According to the results of Liszt and Linke (1975) and Penzias *et al.* (1971), the detection of CS may indicate a density of molecular hydrogen which is on the order of 10^4 cm^{-3}. Thus NGC 7023 appears to be patchy, containing both a hole and a rather dense spot.

III. DISCUSSION

We now turn to speculations regarding the cloud associated with NGC 7023. We will estimate the gas mass of the cloud, and then comment on the elongation and possible dynamics of the system.

TABLE 1

OBSERVATIONS OF ^{13}CO

COORDINATES		$T(^{12}CO)$*	$T(^{13}CO)$*	$\Delta v(^{13}CO)$†	$N(^{13}CO)$
α(1950.0)	δ(1950.0)	(K)	(K)	(km s^{-1})	($\times 10^{15}$) (cm^{-2})
20^{h}59^{m}56^s......	67°51′56″	14.4	3.4	1.6	7.3
20 59 56.......	68 00 56	12.0	3.6	2.6	12.1
21 00 12.......	67 56 26	8.2	< 0.8	...	< 1.2
21 01 00.......	67 54 56	13.6	4.5	1.7	10.6
21 01 32.......	67 18 56	6.3	2.3	1.7	4.4
21 01 32.......	67 48 56	10.7	4.0	1.1	5.7
21 02 04.......	67 57 56	13.9	7.1	1.5	17.2

* Signal-to-noise ratio is ~6 for ^{12}CO and ~3 for ^{13}CO temperatures.

† Full width at half-maximum is accurate to ~1 channel, corresponding to 0.68 km s^{-1} for ^{13}CO.

Two conventional techniques which are used to obtain mass estimates are (*a*) to determine the amount of extinction in the cloud and to convert this value to a hydrogen column density or (*b*) to determine the ^{13}CO column density and to apply a conversion factor for the expected amount of ^{13}CO relative to H_2. When a size for the cloud is assumed, an average space density and total mass may then be estimated. We apply both of these methods in turn to the cloud around NGC 7023.

From a visual inspection of the cloud, we find a ratio r of roughly 3 times as many stars in the hole in the central portion of the cloud as in an equivalent area of the cloud itself. This could provide a good measurement of the total extinction of the cloud, since presumably we are able to look all the way through it (via the hole) for a direct comparison of cloud and background. A typical comparison region outside of the 6 K contour also contains about 3 times the abundance of stars as do lines of sight through the cloud.

Following Dickman (1975), we use $A_v = 4 \log(r) \approx 1.9$, where the factor of 4 depends on the direction in the Galaxy and was extracted from the tabulation of van Rhijn (1929). This value of 1.9 mag is equal to the visual extinction of HD 200775, which has a color excess of $E(B - V) = 0.6$ (Elvius and Hall 1966). Since we would expect the extinction from the entire depth of the cloud to be at least as large as that to HD 200775, we consider our result from star counts to be a lower limit. Correction for an unknown number of foreground stars could raise the extinction significantly.

Using the standard conversion of 1 mag of visual extinction to 2.5×10^{21} cm^{-2} of hydrogen in all forms (Jenkins and Savage 1974), we find that the molecular hydrogen column density is at least 2.4×10^{21} cm^{-2}. This value is compatible with our ^{13}CO column densities, if we adopt a conversion factor for ^{13}CO to H_2 of $\epsilon < 4 \times 10^{-6}$. This is consistent with the value $\epsilon \approx 2 \times 10^{-6}$ derived by Dickman (1975). We use Dickman's value in what follows.

We may use the temperature contours to estimate the size of the cloud and then combine this result with the column density to get an estimate for its mass. The large 10 K contour is roughly 20′ in diameter, which corresponds to an area of some 6.6 pc^2. The product of this area with the estimated H_2 column density then yields a mass of $\sim 600\ M_\odot$ within this contour. Assuming the cloud to be spherical, we have an average density $\rho \approx 2.4 \times 10^{-21}$ g cm^{-3}, corresponding to ~600 cm^{-3} for H_2.

The cloud associated with NGC 7023 is slightly elongated in a north-south direction, as is apparent from both the optical and the radio outlines in Figure 1. The illuminating star and reflection nebulosity are near the center of the northern half of the molecular cloud. The direction of elongation is ~51° from the perpendicular to the galactic plane.

It is interesting to compare the apparent orientation of the cloud with the alignment of any magnetic field in that region of the sky. Since the polarization directions are generally believed to be indicative of magnetic field alignment, we may use the large-scale polarization measurements of Mathewson and Ford (1970) to infer the orientation of the magnetic fields on the line of sight to NGC 7023. We estimate from the published polarization maps that, in the region of the sky where NGC 7023 is located—at $b^{II} \approx 14°$, $l^{II} \approx 104°$—and at distances between 400 and 600 pc from the Sun, the galactic magnetic field is aligned at an angle of 48° ± 6° from the normal to the galactic plane. This is essentially the same as the orientation of NGC 7023.

This coincidence of the inferred directions of the magnetic field and the elongation of the cloud allows for the possibility that the cloud's extension may be due to a flow of matter along the field lines. If there is some force which prevents the main body of the cloud (i.e., where the stars are) from freely falling toward the galactic plane, then there may be some cloud radius R outside of which the gravitational acceleration toward the galactic plane due to the background stellar potential will be greater than the acceleration in the opposite direction due to the cloud itself. Matter beyond this radius can be tidally stripped off. NGC 7023 is about 100 pc above the plane; the acceleration due to the Galaxy is $g \approx 2.5 \times 10^{-9}$ cm s^{-2} (Spitzer 1968), and the component of this

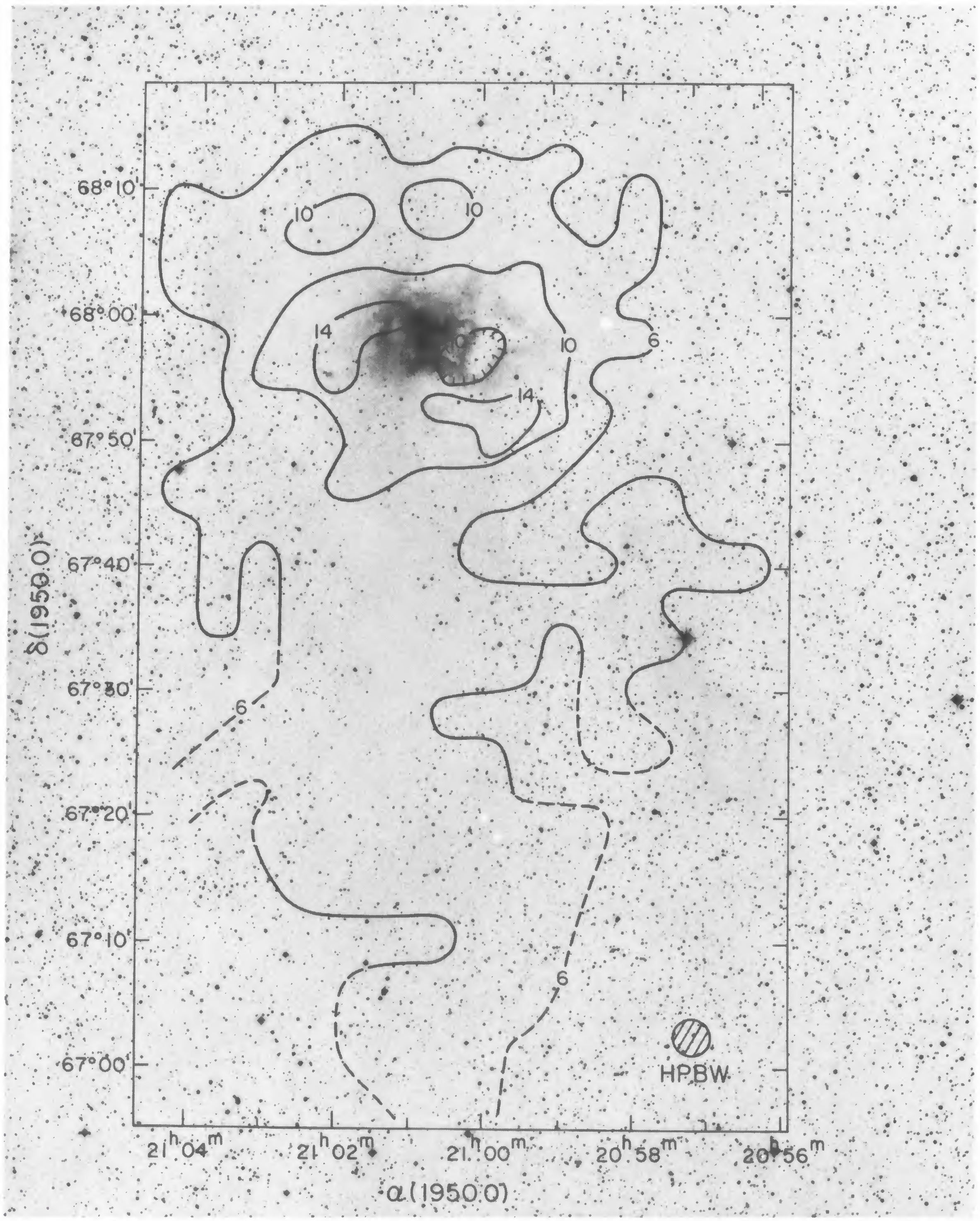

FIG. 1.—The ^{12}CO temperature contours are shown superposed on the red plate of NGC 7023 from the Palomar Observatory Sky Survey. Dotted lines indicate regions where double-beam, rather than single-beam, spacing was used in the CO mapping. The tick-marked region encloses ^{12}CO corrected temperatures of 6–7 K. Region A is the area between $\alpha = 21^h01^m75–21^h02^m25$ and $\delta = 67°52'–67°58'$. Region B is between $\alpha = 20^h59^m0–21^h00^m5$ and $\delta = 67°52'–67°58'$. Region C includes all points south of $\delta = 67°40'$ (see text for discussion).