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A LARGE MOLECULAR CLOUD IN LUPUS FAR FROM THE GALACTIC PLANE

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ABSTRACT

A wide-latitude CO survey of the fourth Galactic quadrant revealed a molecular cloud fairly far from the Galactic plane between $b = 3°$ and $5°.5$ at $l \approx 325°$, with a radial velocity of -41 km s^{-1}, much larger than is characteristic of most local, high-latitude gas. The near kinematic distance is 2.9 kpc, placing the cloud 150–280 pc above the Galactic plane, the largest displacement at which a molecular cloud has yet been detected. The mass of the cloud as derived from the CO observations is $\sim 10^5\ M_{\odot}$, similar to the mass of the large cloud associated with the Orion Nebula, and its gravitational potential energy is $\sim 7 \times 10^{50}$ ergs.

A conspicuous hole in the longitude-velocity distribution of CO in the plane below the cloud, with a projected diameter of ~ 200 pc, suggests that a single event may have created both, multiple supernova explosions and stellar winds being the most plausible candidate. The tilted distribution of molecular clouds surrounding the hole is similar to the distribution of molecular clouds in Gould's Belt, but the smaller scale size and expansion age of the hole implies that it was formed more recently than Gould's Belt.

Subject headings: galaxies: Milky Way — galaxies: structure — interstellar: molecules

I. INTRODUCTION

In the general vicinity of the Sun and the solar circle, most of the molecular gas in the Galaxy is confined to a disk with a mean half thickness at half maximum of ~ 70 pc (Bronfman *et al.* 1987). Fairly massive, local molecular clouds, associated with the young objects in Gould's Belt, such as the complexes in Orion, Taurus, and Ophiuchus, although as much as 25° from the Galactic equator, are still less than 200 pc from the plane. This paper describes the detection of a large molecular cloud at a distance of more than 200 pc from the Galactic plane, situated above a prominent hole in the CO distribution in the plane. The physical parameters of both the cloud and the hole are derived from the CO observations, and possible causes for their formation are discussed. Other holes and shells also appear in the molecular gas in the Milky Way; one is associated with the λ Ori H II region (Maddalena *et al.* 1986), another with the W44 supernova remnant (Dame 1984), but both are smaller than the hole discussed here. Larger holes may exist in the fourth Galactic quadrant (see § II).

In the distribution of neutral hydrogen, holes, and filamentary structures in the form of arcs and shells with diameters of a few hundred pc and expansion velocities of 10–20 km s^{-1} have been observed in the Milky Way and in external galaxies (Heiles 1979, 1984; Shostak and Woerden 1983; Brinks 1984). H I supershells with diameters greater than 1 kpc also have been observed (Heiles, 1979; Brinks 1984). Holes less than 300 pc in diameter may be correlated in position with OB associations and H II regions.

II. OBSERVATIONS AND RESULTS

Observations were made during 1985–1986 with the Columbia Southern 1.2 m millimeter-wave Telescope at Cerro Tololo, Chile (Cohen 1983) of the CO $J = 1 \rightarrow 0$ line at 115 GHz. The beamwidth of the telescope is 8'.8 (FWHM) at this frequency; data were taken either at full resolution or lower by a factor of 2 or 4 by automatically stepping the telescope through a square array of positions during an observation. The array spacing was 0°.125 (slightly less than one beamwidth), which gives a synthesized beam of 0°.5 on a side with a 4×4 array and 0°.25 on a side with a 2×2 array. Data with 0°.5 resolution were taken as part of a general wide-latitude survey of the fourth quadrant, in which the cloud described here was first detected.

Position switching was used against reference positions previously shown to be free of CO emission stronger than 0.03 K; the rms noise in the spectra is 0.1 K or less. Calibration of the telescope was made with a standard, room-temperature blackbody chopper wheel that corrects for atmospheric attenuation. A further correction for main beam efficiency was applied to obtain intensities that agree with those of the wide-latitude survey of Dame and Thaddeus (1985), used to derive the conversion from integrated CO intensity to H_2 column density (Bloemen *et al.* 1986; see § III*b*). The intensities are all within 5% of those of all other Columbia 1.2 m data reported since 1980. Bronfman *et al.* (1987) recently estimated that these intensities are $\sim 20\%$ below the true radiation temperature (i.e., the physical temperature of a blackbody that just fills the main beam), but here, for consistency, we adopt the scale used for the CO mass calibration.

The superheterodyne receiver, whose mixer was a liquid-nitrogen–cooled Schottky barrier diode, had a double-sideband receiver noise temperature of ~ 180 K. Pointing was established to better than 1' by scanning the Sun and by observing stars through a small co-aligned optical telescope. The spectrometer consisted of a filter bank of 256 channels,

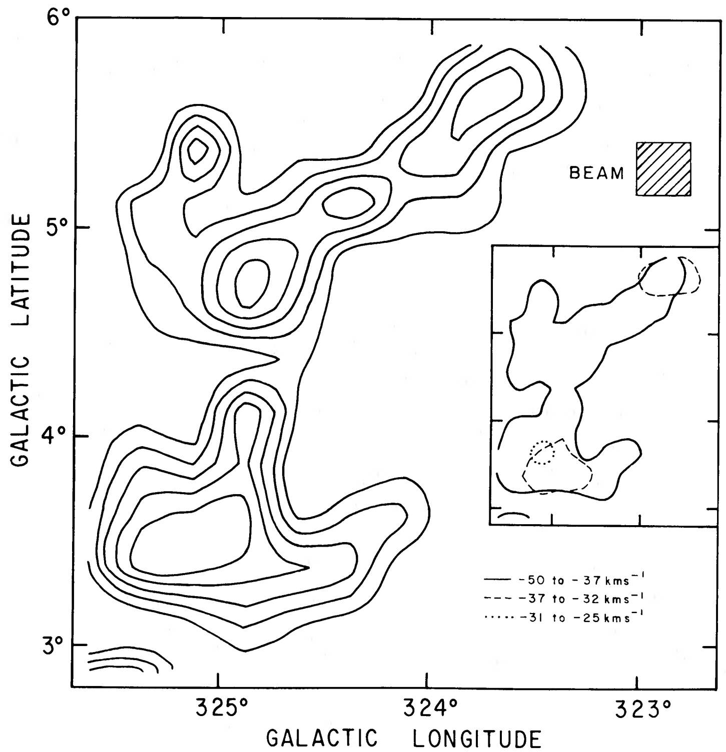

FIG. 1.—Map of the high-z cloud at an angular resolution of 0°.25. The inset shows the extent of the various velocity components (at −42, −34, and −29 km s^{-1}). Contour interval is 1 K km s^{-1}.

each 0.5 MHz wide, which at 115 GHz provides a velocity resolution of 1.3 km s^{-1} and a spectral range of 332 km s^{-1}.

The cloud above the plane was observed fully at a resolution of 0°.25 and partially at 0°.125 to better determine its structure. Figure 1, a map of the velocity integrated CO intensity from the 0°.25 data, clearly shows the two major parts of the cloud. The lower part consists of three velocity components, at about −42, −34, and −29 km s^{-1} (Fig. 1, inset). The first is extended over the whole cloud and has a velocity gradient from −42 km s^{-1} at 324°.5 to −40 km s^{-1} at 325°.4; its line width varies from ~9.3 km s^{-1} in the center to ~3 km s^{-1} in the outer regions. Composite line profiles were made by adding spectra within a square region centered on a component, and Gaussian profiles were then fitted to them (see Tables 1 and 2).

The upper part of the cloud has an elongated shape with four emission peaks. The CO emission has a fairly constant velocity of −41 km s^{-1} over the cloud, apart from the uppermost peak at a velocity of about −36 km s^{-1}. The line width is ~5 km s^{-1}.

Figure 2 is a map of the CO intensity from the 0°.5 resolution data integrated over the velocity interval of the hole in the CO distribution below the cloud, and Figure 3 is a longitude-

TABLE 1

PHYSICAL PARAMETERS OF THE TWO MAJOR COMPONENTS OF THE CLOUD

Cloud	z (pc)	v[a] (km s^{-1})	Δv[a] (km s^{-1})	R (pc)	M_{CO} $10^3\ M_\odot$	M_{vir} $10^3\ M_\odot$	W_{pot} 10^{50} ergs
Lower	170–210	−41.5	7.8	28.1	54.0	358	2.4
Upper	235–285	−40.0	6.9	30.7	58.9	306	4.5

[a] v is the center velocity, and Δv the FWHM of the composite spectral line.

TABLE 2

PHYSICAL PARAMETERS OF THE VELOCITY COMPONENTS OF THE CLOUD

Cloud	z (pc)	v[a] (km s^{-1})	Δv[a] (km s^{-1})	R (pc)	M_{CO} $10^3\ M_\odot$	M_{vir} $10^3\ M_\odot$	W_{pot} 10^{50} ergs
Lower: a	170–210	−41.6	7.1	28.1	43.8	297	2.0
b	165–190	−33.6	5.2	12.2	4.2	69	0.17
c	180–190	−28.9	4.0	7.0	1.5	23	0.06
Upper: a	235–270	−40.5	5.5	28.1	47.4	178	3.5
b	270–285	−36.3	4.7	12.2	9.6	56	1.0

[a] v is the center velocity and Δv the FWHM of the composite spectral line.

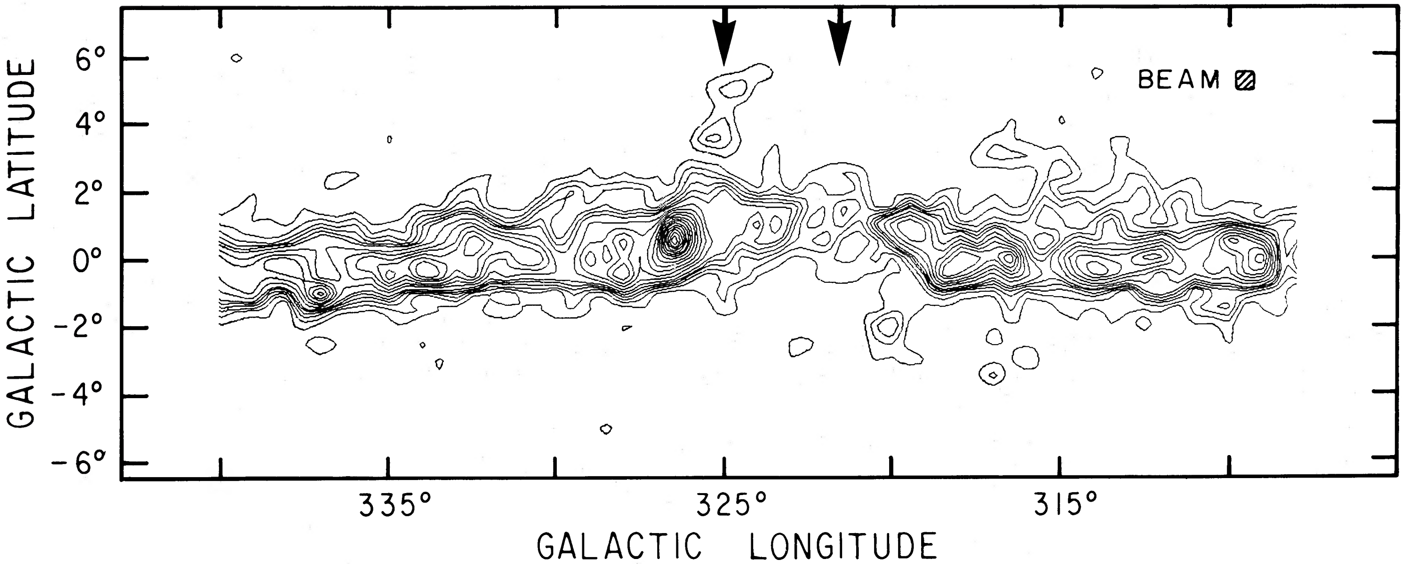

FIG. 2.—Integrated CO-intensity between the velocities −44 and −38 km s^{-1} at an angular resolution of 0°.5. The arrows mark the position of the cloud and the hole. Contours are at 0.8, 1,8, 2.8, 3.8, 4.8, 5.8, 7.8, 9.8, etc., K km s^{-1}.

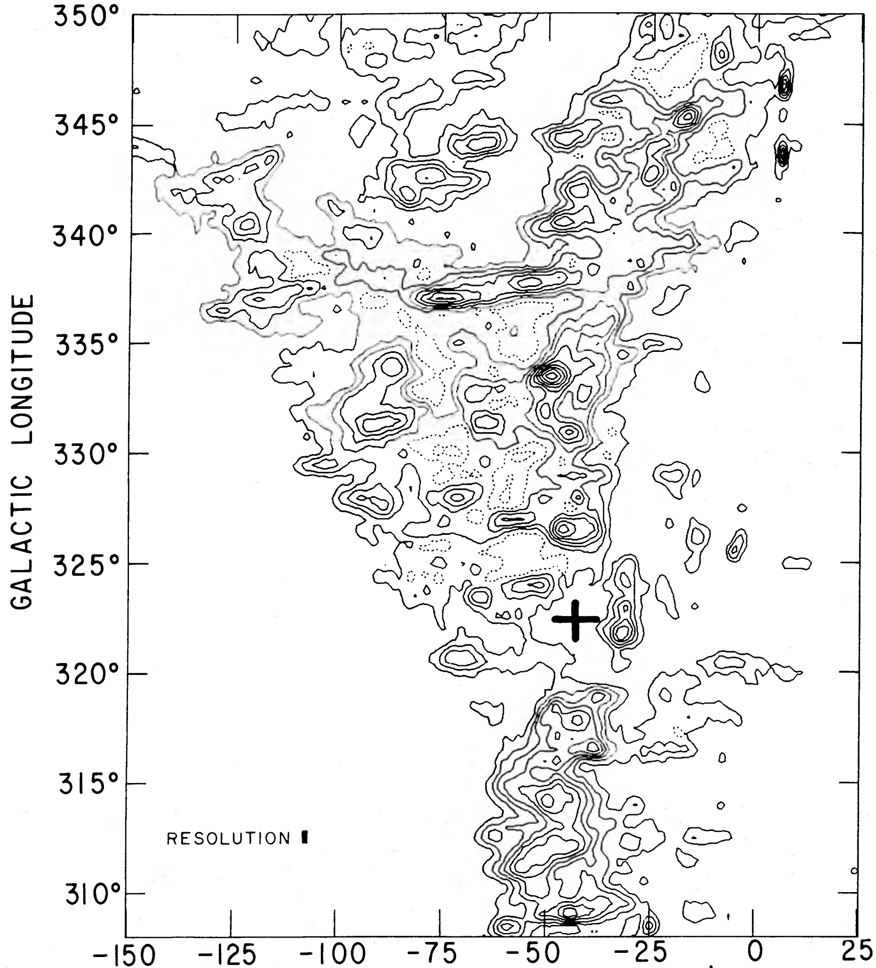

FIG. 3.—Longitude-velocity diagram at $b = 0°$ from the 0°.5 resolution data, to give an overview of a large part of the fourth Galactic quadrant. The hole in the CO distribution is visible at $l \approx 322°$ and $v = -41$ km s^{-1} and is marked by a cross. The massive Scutum-Centaurus arm is the strong feature extended at all longitudes between the velocities −60 and −10 km s^{-1}. Its tangential point is situated between $l \approx 308°$ and 315°. Contour interval is 0.5 K. Dotted lines are downgoing contours.

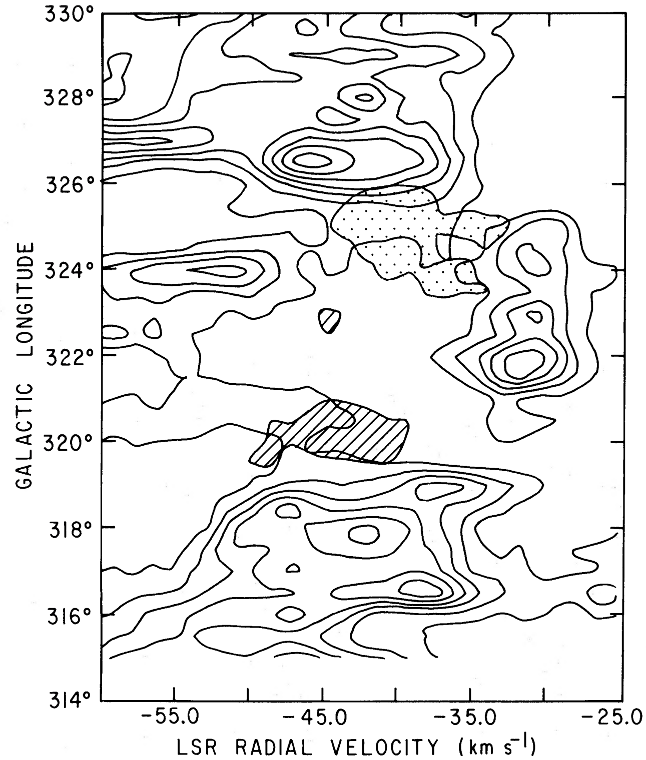

FIG. 4.—Enlargement of the area in Fig. 3 where the hole is situated. The regions marked by dots and solid lines are the CO emission integrated in latitude over the cloud above the plane and the two clouds below the plane, respectively (Fig. 2), and then superposed on the l-v diagram in the plane.

velocity diagram of the CO emission in the plane. The hole, clearly visible between 320° and 325° in longitude and -55 and -35 km s^{-1} in velocity, is situated in the near side of the massive Scutum-Centaurus spiral arm (Fig. 3). Four other holes may exist in the arm: at 318° and -65 km s^{-1}, at 323° and -70 km s^{-1}, at 325° and -55 km s^{-1}, and at 328° and -55 km s^{-1}, but clouds far from the Galactic plane associated with these have not yet been detected. The hole in the CO distribution is the only one observed in the Galaxy up to now that is associated with a molecular cloud at a large distance from the plane. Apart from the high displacement cloud, two other clouds below the plane, one quite small, may also be related to the hole (Fig. 2). Figure 4 shows these three clouds in projection superposed on the longitude-velocity distribution of the CO emission at $b = 0°$. A few other clouds near the tangential region of the Scutum-Centaurus arm between 315° and 318° (see Fig. 2) are situated ~ 150 pc above and below the plane.

III. DISCUSSION

a) Distance

At an LSR radial velocity of -41 km s^{-1}, the high displacement cloud is almost certainly not local, and its kinematic distance should be a good approximation to the true distance. Using Burton and Gordon's (1978) rotation curve (with $R_0 =$ 10 kpc and $\theta_0 = 250$ km s^{-1}), the near distance is 2.9 kpc and the far distance 13 kpc; the far distance can almost certainly be ruled out since it would imply a location more than 1 kpc above the plane. The near distance gives a satisfactory size for the cloud, that, relative to its CO line width, fits the relation derived by Dame *et al.* (1986) for Galactic molecular clouds. On the ESO *J* plate the cloud does not appear as a dark nebula, a result consistent with a distance of 2.9 kpc because most stars seen on the plate in this direction probably are foreground (but see also the discussion in § IV). Since the hole in the plane is situated among the molecular cloud complexes in the near side of the Scutum-Centaurus spiral arm (Bronfman *et al.* 1987), an association between the cloud and the hole also implies a near distance. Because of the peculiar history of the cloud its radial velocity may not be the result of Galactic circular rotation alone, and its kinematic distance may therefore be misleading. However, the similar velocities of the cloud and the hole and the apparent association of the two again suggest that the kinematic distance of the cloud is close to the true distance.

At 2.9 kpc, the cloud is extended from 150 to 280 pc above the plane, which, to our knowledge, is the largest displacement at which a molecular cloud has been detected. The projected diameter of the hole is ~ 200 pc.

b) Mass

The mass of a cloud at a known distance can be estimated from CO observations by using the ratio between molecular hydrogen column density, $N(H_2)$, and the CO velocity integrated line intensity, W_{CO}, which Bloemen *et al.* (1986) obtained from an intercomparison of CO, H I, and γ-ray surveys: $N(H_2)/W_{CO} = 2.8 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$. This ratio is apparently constant from 4 to 10 kpc from the Galactic center and will therefore be adopted here. The mass of the high-z cloud then can be determined immediately from the relation

$$M_{CO}/M_\odot = 1.83 \times 10^{-3} I_{CO}\, d^2 , \quad (1)$$

where I_{CO} is the apparent CO luminosity (the velocity-integrated line intensity integrated over the subtended solid angle, in units of K km s^{-1} deg^2) and d is the distance to the cloud in pc; a mean atomic weight per H atom of 1.36 is assumed. In this way, the total mass of the cloud is calculated to be $\sim 1.1 \times 10^5\ M_\odot$. Tables 1 and 2 present a breakdown of the cloud into its main components, derived from observations at the higher resolution.

The virial mass of the cloud is

$$M_{vir} = 5R(\Delta v_{FWHM})^2/(8G \ln 2) , \quad (2)$$

where R is the radius, Δv_{FWHM} the CO line width at half-maximum, and G the gravitational constant, on the assumption of a homogeneous, spherical cloud with a Maxwellian velocity distribution in virial equilibrium. The contribution of magnetic fields or any other source of pressure to the internal energy is assumed to be negligible. Equation (2) becomes $M_{vir}/M_\odot = 209.6\ R\ (\Delta v_{FWHM})^2$, if R is in pc and Δv_{FWHM} in km s^{-1}. Since the size of the cloud in the line of sight is not known, the radius was taken to be $R = (A/\pi)^{1/2} d$, where A is the solid angle of the cloud and d the distance. The virial masses (Tables 1 and 2) are found to be $\sim$5–6 times larger than masses determined from the CO intensity, implying that the components are not in virial equilibrium, i.e., are not gravitationally bound.

c) Energy and Time Scale

Let us assume that both cloud and hole were formed by a single event in the Galactic plane, and attempt to estimate the energy of this event and when it occurred. The cloud's potential energy, i.e., the energy needed to raise it from the Galactic plane to its present position, is readily calculated if the gravitational potential perpendicular to the plane is known. From the potential derived by Bahcall (1984) for the solar neighborhood, scaled by a factor of 1.8 to correct for the greater total mass density 2 kpc inward from the Sun (Mihalas and Binney 1981, p. 22), and from the mass and displacement just derived, the total energy needed is found to be $\sim 7 \times 10^{50}$ ergs (see Tables 1 and 2); since the present velocity of the cloud perpendicular to the plane is unknown, this energy is only a lower limit. Assuming the cloud is in free fall, and starting from its present position at rest, the free-fall time and the velocity of the cloud as it crosses the Galactic plane are readily calculated. The time, also an estimate of how long ago the event occurred, is $\sim 15 \times 10^6$ yr. If, however, the cloud is not now at its largest distance from the plane, the time scale obviously can be either larger or smaller. The velocity of the cloud as it crosses the plane is ~ 25 km s^{-1}.

The expansion time of the hole can be calculated from its projected diameter and velocity of expansion; its diameter is ~ 200 pc and, on the assumption that the expansion velocity, ~ 10 km s^{-1}, is half the velocity width in the plane, the time scale is $\sim 10 \times 10^6$ yr, in satisfactory agreement with the free-fall time. The energy needed to create the hole can be estimated from its size and expansion velocity and from an assumed average molecular density in the region before the hole was created. The average density at 8 kpc from the Galactic center in the fourth quadrant has been estimated to be ~ 1 cm^{-3} (Bronfman *et al.* 1987). The size of the hole in the plane (~ 200 pc), the scale height of the gas at this galactocentric distance (~ 70 pc; Bronfman *et al.* 1987), and the expansion velocity (~ 10 km s^{-1}) yield a mass of $\sim 4 \times 10^5$ $M_\odot$ and energy of $\sim 4 \times 10^{50}$ ergs. The average density in the region probably was larger than that estimated in the axisymmetric analysis of Bronfman *et al.* (1987) because the hole is situated among molecular cloud complexes in a spiral arm, so both the mass and the energy probably are lower limits.

d) *Formation of Cloud and Hole*

The potential energy of the cloud and the energy needed to create the hole are comparable to the kinetic energy of a supernova remnant (SNR) or a stellar wind from an O star over its life (Chevalier 1977; Lamers 1983). The energy of the event itself, however, would undoubtedly have to be larger than this—and probably much larger—because the efficiency of conversion into the ordered kinetic energy of the dense molecular gas is probably low. For example, the outflow centered on the older subassociations of OB stars in Orion which Cowie, Songaila, and York (1979) interpreted as the result of multiple supernova explosions (~ 10) or stellar winds (or both) operating over a period of $\sim 3 \times 10^6$ yr has apparently not been strong enough to accelerate the Orion molecular clouds to more than a small fraction of the 25 km s^{-1} determined for our cloud. Many supernovae (SNs) or winds from many O stars (or both) probably are therefore required to explain the large energy involved in the creation of the cloud and hole. However, many SNs seem to occur in a large molecular cloud during its lifetime. A simple estimation, using the Galactic SN frequency of 1 every 30 yr (Lamers 1983), of which half are associated with large molecular clouds (Huang and Thaddeus 1986), together with the number of molecular clouds in the Galaxy with $M > 10^6$ $M_\odot$, ~ 200 (Dame *et al.* 1986), gives ~ 1 SN per 10^4 yr per cloud. As many as 10^3 SN explosions may therefore be associated with a large molecular cloud assuming it lives for as long as 5×10^7 yr.

The cloud and the hole are situated in the very massive Scutum-Centaurus spiral arm (Bronfman *et al.* 1987), which contains many large molecular complexes, H II regions, and OB associations. It is plausible that a large OB association was formed in this region more than 10^7 yr ago, and the hole and the cloud were formed by interaction with supernova explosions or stellar winds or both. No radio continuum emission now seems to be associated with the hole (Haynes, Caswell, and Simons 1978; Haslam *et al.* 1982), but six younger SNRs exist in its general direction, five below the plane (Haynes, Caswell, and Simons 1979). The shape of the hole, its edges turned slightly upward (Fig. 2), and the existence of the cloud high above the plane suggest that the event or events that caused them may have occurred largely below the plane. The SNRs seen today may possibly be remnants of less massive or more recently formed stars in an OB association created slightly below the plane more than 10^7 yr ago.

The cloud and the hole are situated in a region in the *l-v* diagram where several other holes are seen and where the distribution of CO emission seems to be "disturbed," possibly due to enhanced activity of star formation, triggered by some larger scale event in this part of the Scutum-Centaurus spiral arm.

IV. CONCLUDING REMARKS

Several questions concerning the formation and appearance of the cloud and the hole remain to be answered. We state here some of the more interesting ones and suggest some further observations.

1. The two clouds above and below the plane situated at the edges of the hole (Fig. 2), form a distribution of molecular clouds reminiscent of Gould's Belt, the local expanding ring of stars and interstellar clouds tilted $\sim 20°$ to the Galactic plane, whose diameter is ~ 700 pc and whose expansion age is $\sim 6 \times 10^7$ yr (Stothers and Frogel 1974; Lindblad *et al.* 1973; Olano 1982). It has already been suggested that Gould's Belt, too, was the consequence of interaction of SNs and stellar winds with the interstellar medium (Olano 1982). The Orion, Taurus, ρ Oph, and Lupus molecular clouds may all be part of the expanding ring (Dame *et al.* 1987). The hole discussed in this work has a smaller diameter and smaller expansion age than Gould's Belt, implying that we are seeing a younger version of Gould's Belt. Some clouds in Gould's Belt (Orion, ρ Oph, and Lupus) have regions of active star formation, but because the cloud discussed here unfortunately has not been included in higher resolution continuum surveys it is not clear whether it is forming stars or not. Continuum and optical surveys of the area are needed.

2. The cloud poses interesting questions with respect to the acceleration and confinement of large quantities of molecular gas and to the formation of molecules under such conditions. Can molecules survive the acceleration phase, or will they be dissociated and later recombined? If the latter, this cloud could be a fairly young object.

3. The cloud is not seen as a dark nebula on the ESO Schmidt plates, presumably because of its distance and the large number of foreground stars in this direction; the comparably massive cloud associated with W50, at a similar distance and also below the plane, however, is easily distinguished on the POSS prints (Huang, Dame, and Thaddeus 1983). One explanation of this difference is that the number of foreground stars toward the cloud discussed here may be higher than toward W50, a second is that the cloud here may have a low

extinction (low dust content) or a high CO abundance (or both) because of its peculiar history. Judging from the H I data, the extinction associated with diffuse foreground gas is probably less than ~ 1 mag; not a great deal more would be required to account for the absence of the cloud as a dark nebula.

4. Our cloud may be related to the shells seen in H I surveys (Heiles 1979, 1984) and, on a larger scale, to Galactic fountains (Bregman 1980) and mass loss from the Galaxy. Because the cloud is situated fairly close to the Galactic plane detection of an associated H I shell would be difficult.

5. The cloud was easily detected in a CO survey with a resolution of 0°.5. With the present resolution of interferometers at 115 GHz ($\sim 10''$) similar clouds should be detectable in external galaxies, especially those seen edge on, to a distance of 2.5 Mpc; holes similar in size to that discussed here might be detected even farther.

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