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THE MOLECULAR COMPLEXES IN ORION

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ABSTRACT

Line emission from CO at 2.6 mm is observed over an area of 28 square degrees in the Orion region. Most of the emission comes from two giant molecular complexes, roughly associated with Ori B and Ori A. The latter provides the best example of a giant molecular complex at the end of a sequence of OB association subgroups of decreasing age. This complex is apparently rotating with an angular velocity 4.5×10^{-15} s^{-1}, but in a direction opposed to the Galactic rotation. The apparently denser parts of the cloud are rotating at a somewhat greater angular velocity. The total mass of the molecular gas, derived from the observations, is $2 \times 10^5\ M_\odot$, implying that roughly half the matter in this region is in the form of molecular hydrogen.

Subject headings: interstellar: molecules — nebulae: general

I. INTRODUCTION

Though much of the study of the Orion region has focused on the spectacular H II regions, considerable effort has been devoted to understanding the structure and evolution of the region as a whole. The first complete 21 cm survey in Orion was by Menon (1958), who found the total mass of hydrogen to be about $10^5\ M_\odot$, and a velocity pattern which was interpreted as being indicative of an expanding shell. From a higher resolution study, Gordon (1970) concluded that the predominant velocity pattern was one of rotation rather than expansion. Tucker, Kutner, and Thaddeus (1973, hereafter TKT) concluded that a large fraction of the material is in molecular form, based on observations of 2.6 mm CO emission from the dust cloud L1630 (see Fig. 1*a*). In this paper we present observations which reveal the full extent of the molecular matter in Orion.

The region studied, sketched in Figure 1*a*, lies primarily within the diffuse emission of Barnard's loop. Besides the many emission and reflection nebulae, there are a number of dust clouds; the largest are L1630, which extends northeast from Ori B for 5°, and L1641, running northwest and southeast from Ori A for 8° parallel to the Galactic equator, and along Gould's Belt (Stothers and Frogel 1974). The four subgroups of the OB association I Ori extend from the Trapezium cluster (Id Ori) to the northwest, in increasing order of age, along a line close to the apparent axis of L1641 (see Fig. 2). One of the most interesting questions raised by the current observations is the relationship of the gas to the structure and formation of the OB association.

II. OBSERVATIONS

The observations for this study were done on two instruments, the 16 foot (5 m) antenna of the Millimeter Wave Observatory, Fort Davis, Texas,[1] and a 4 foot (122 cm) telescope at Columbia University. The observations were complementary in the sense that the Columbia telescope was used to obtain a completely sampled, low-resolution (8′ beamwidth) map, while the Texas observations, done before the completion of the 4 foot telescope, produced a generally sparsely sampled map, but with higher spatial (2.′6 beam) and velocity (0.65 versus 2.6 km s^{-1}) resolution.

The salient features of the CO intensity distribution are shown in Figures 1*b* and 1*c*. There are two major molecular complexes which approximately follow the large dust clouds. The total area covered by these two complexes is about 28 square degrees. A comparison of Figures 1*b* and 2 shows that we have not detected any CO emission over the I*a* subgroup and a large portion of the I*b* subgroup. However, these regions have been sparsely sampled, and though we can probably rule out the existence of large molecular complexes in these regions, there may still be some molecular material we have not detected.

[1] The Millimeter Wave Observatory is operated by the Electrical Engineering Research Laboratory, the University of Texas, Austin, with support from the National Aeronautics and Space Administration, the National Science Foundation, and McDonald Observatory.

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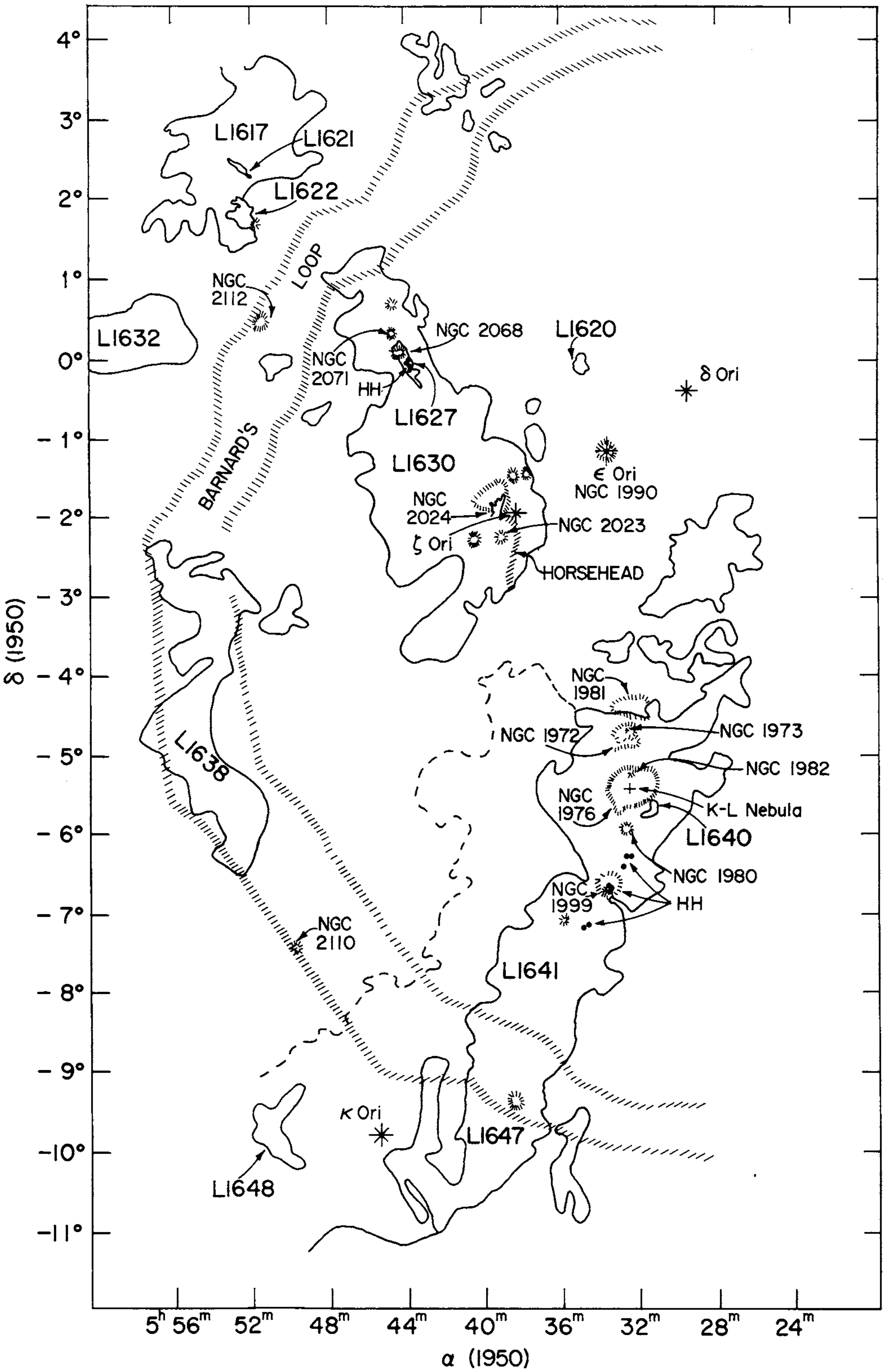

FIG. 1.—Summary of CO observations in Orion. (*a*) A sketch of the salient features visible on the Palomar Sky Survey prints. The hatched boundaries indicate the boundaries of optical emission or reflection nebulosity. The approximate boundaries (from the blue print) of dust clouds, designated by Lynds (L) numbers, are given in solid lines; *dashed line*, a lower extinction edge of L1641. Herbig-Haro objects are designated by HH.

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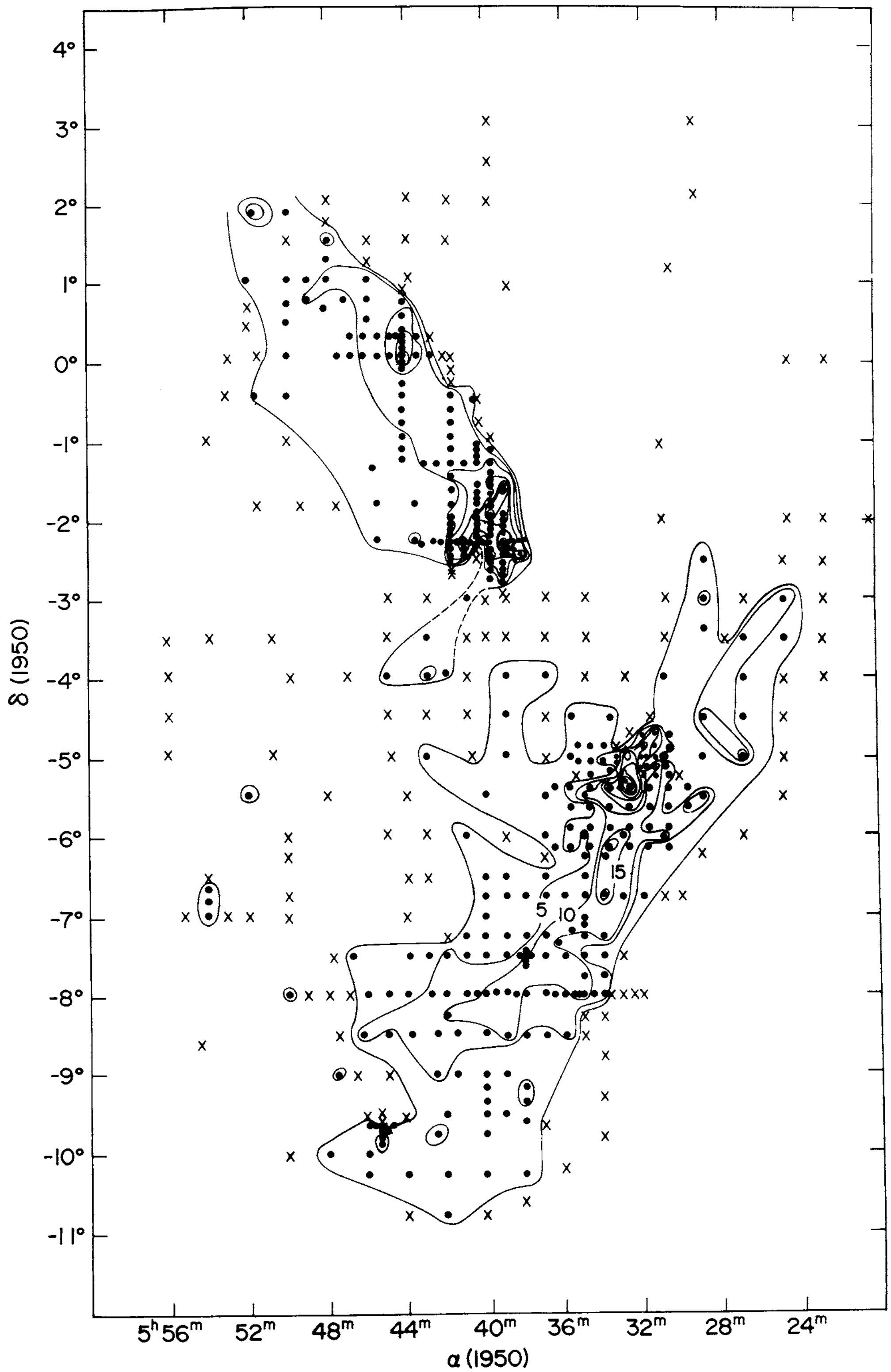

FIG. 1.—(*b*) CO distribution in the Orion region from the Texas (16 foot) observations. Intensities are given as line radiation temperatures, corrected for atmospheric attenuation and beam efficiency as described by Davis and Vanden Bout (1973). (T_R in the direction of the KL nebula is 75 K.) *Filled circles* (approximately the HPBW), CO detections. *Crosses*, negative results, corresponding to upper limits of 1–2 K. (In the vicinity of the KL nebula, the density of points was too great to show all positions observed.) The contour interval is 5 K in peak radiation temperature, with the outermost contour representing the limit of detections.

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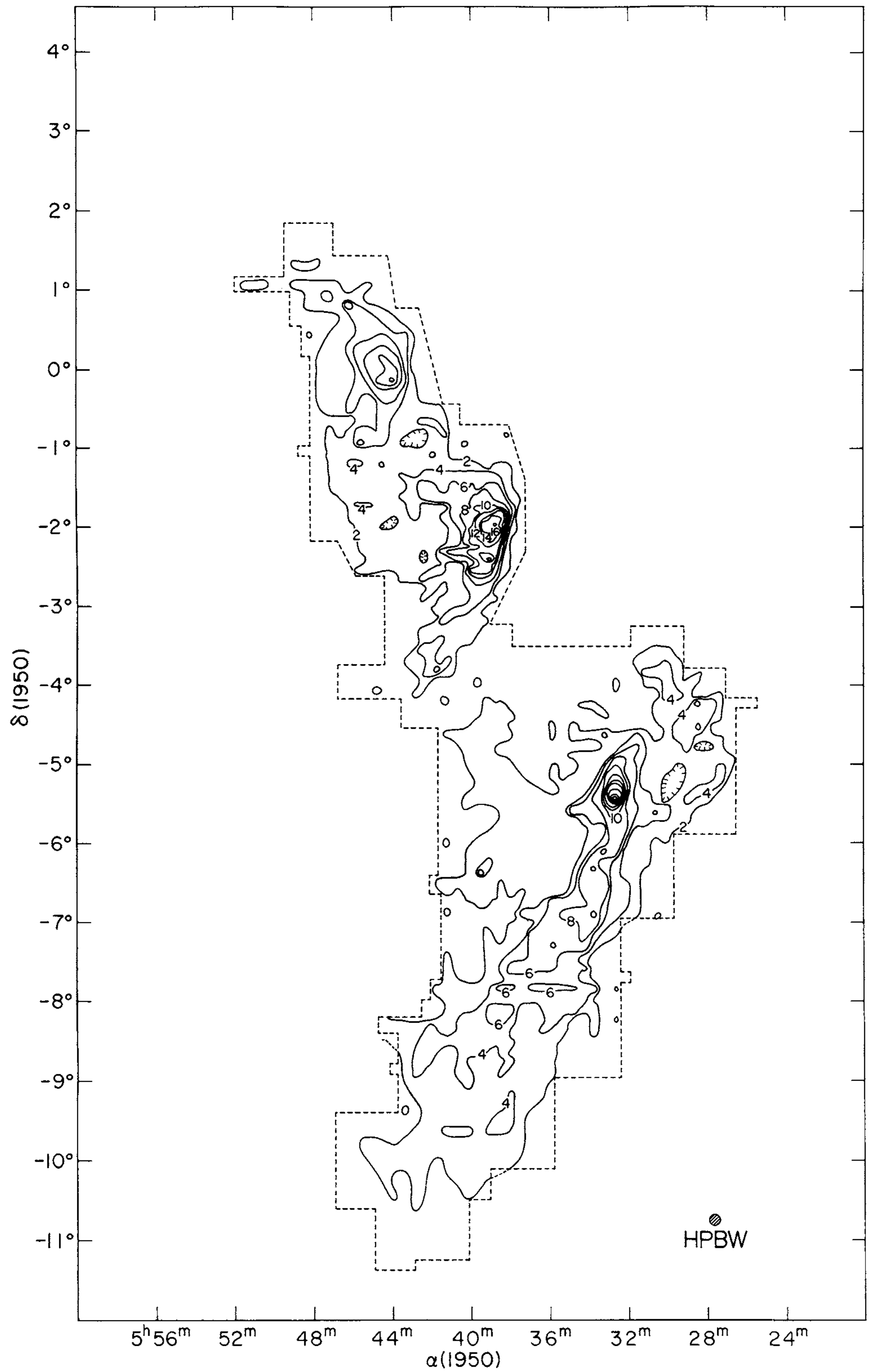

FIG. 1.—(*c*) The Columbia (4 foot) observations. CO intensity distribution from the mapping at one beamwidth intervals, and half-beamwidth intervals in the vicinity of peaks. The contours are of peak radiation temperature. No correction has been made for beam and filter dilution.

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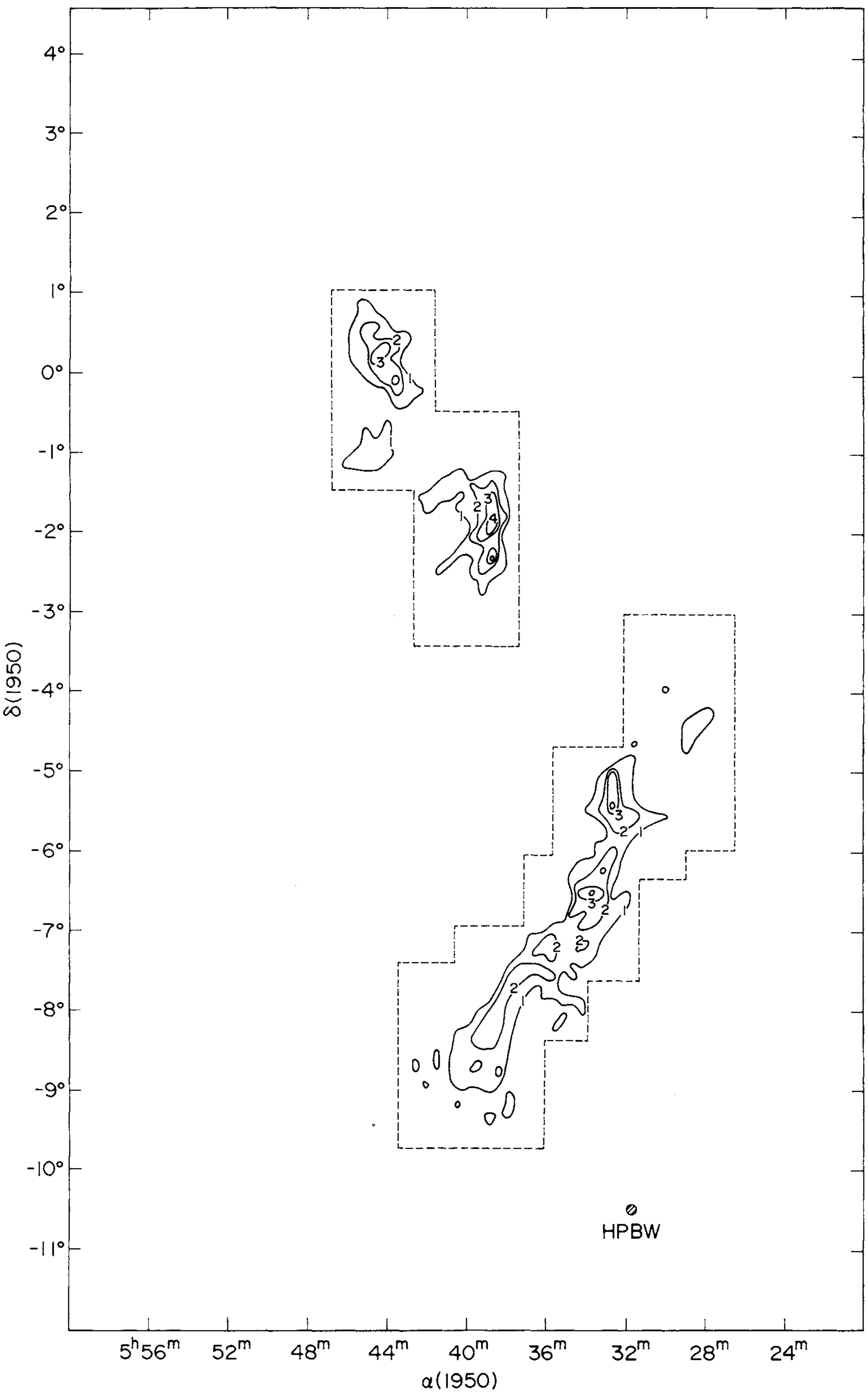

FIG. 1.—(*d*) ^{13}CO intensity distribution from the Columbia observations

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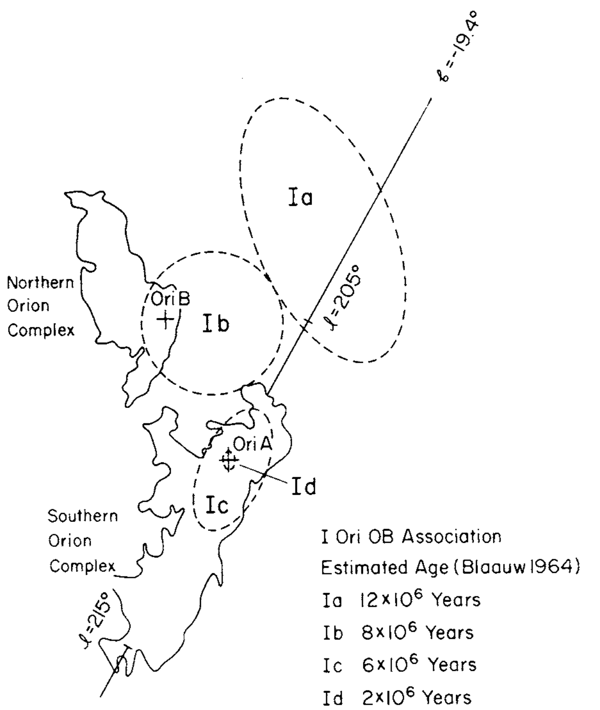

FIG. 2.—The relationship between the Orion molecular complexes and the four subgroups of the OB association I Ori. The molecular complexes are as delineated in Fig. 1*c*. *Dotted lines*, boundaries which roughly enclose the subgroup members as identified by Blaauw (1964).

In the northern complex, as discussed by TKT, the strongest CO emission is at the southern end, in the vicinity of Ori B and the reflection nebula NGC 2023, and at the northern end, in the direction of NGC 2068 and NGC 2071 (which have been studied in detail by Lada *et al.* 1974). The line profiles are characterized by considerable velocity structure, but there is no systematic shift in velocity across the cloud. Most of the CO emission occurs close to 9 km s^{-1} (LSR), but there is, in addition, a 4 km s^{-1} feature covering a 1 square degree area, roughly centered at 5^h40^m, $-1°30'$. In the southern complex, the strongest CO emission contours follow Orion's Sword and then turn to the southeast below NGC 1999. Details of the northern half of the sword region are discussed by Kutner, Evans, and Tucker (1976).

The most striking difference between the northern and southern complexes is that the lines in the southern one show a systematic velocity shift. The velocity gradient along the apparent axis of the cloud (at $b^{II} = -19.4°$) is shown in Figure 3. Over the range $207° \leq l^{II} \leq 214°$, the average velocity gradient is 0.135 km s^{-1} pc^{-1} (assuming a distance of 500 pc). Weak CO emission is observed beyond $l^{II} = 214°$, but there is a rather abrupt halt to the gradient at this point. The sense of the gradient is such that the northern end has a greater positive velocity.

Observations were also made with both telescopes of the isotopic species $^{13}C^{16}O$. A completely sampled

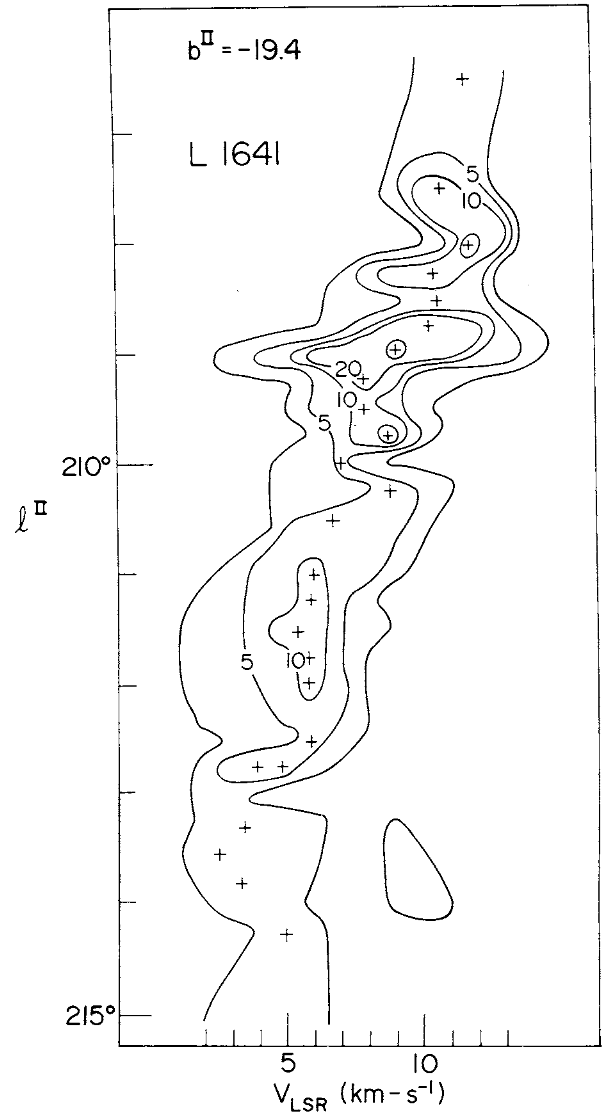

FIG. 3.—The velocity gradient in the southern complex (from the Texas observations). These contours are of CO radiation temperature as a function of l^{II} for points, a quarter-degree apart, lying near $b^{II} = -19.4°$. The crosses represent the velocity of the peak temperature in each spectrum.

map made with the Columbia telescope is shown in Figure 1*d*. In the northern complex, the ^{13}CO emission shows two distinct concentrations around the regions of strongest CO emission. In the southern complex, a very elongated structure is observed. The Texas system had a better sensitivity for narrow lines, and some of the Texas ^{13}CO detections are beyond the boundaries of the Columbia observations.

III. DISCUSSION

These observations reveal the existence of two major molecular complexes in the Orion region. It is generally

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assumed that the dominant constituent in such clouds is molecular hydrogen, and that the CO serves as a fairly good tracer for the H_2. We can therefore use the CO observations to trace the distribution and kinematics of the molecular material in these complexes. We estimate the total mass, first by finding the CO column densities. For those positions where ^{13}CO spectra were obtained, the ^{13}CO column density N_{13}, is estimated on the assumption that both CO isotopes have the same excitation temperature. For positions away from the emission peaks we find an average $N_{13} = 1 \times 10^{16}$ cm^{-2}. At such positions trapping in the optically thick CO will probably cause the CO to have a higher excitation temperature than the ^{13}CO (e.g., Goldreich and Kwan 1974), resulting in an underestimate of N_{13}, perhaps by as much as a factor of 2 (Dickman 1976). However, Dickman finds that if N_{13} is computed as above and one takes the usual gas-to-dust ratio, then, over the visual extinction range 1 to 8 mag, $N_{H_2} \approx 5 \times 10^5 N_{13}$. This yields an average value $N_{H_2} = 5 \times 10^{21}$ cm^{-2}, and mass estimates of $6 \times 10^4\ M_\odot$ and $1 \times 10^5\ M_\odot$ for the northern and southern complexes. For comparison, a rough estimate of the mass of the southern complex can be obtained from the virial theorem, using the kinetic energy of rotation. Some numerical factors depend on the cloud shape, but the result is about $1 \times 10^5\ M_\odot$.

It is significant that, although the molecular complexes are not delineated in 21 cm intensity maps, the 21 cm and CO observations of the velocity gradient in the southern complex agree very well in magnitude, sense, and extent. This means that there must be a small residual concentration of atomic hydrogen associated with the cloud, either intermixed with the H_2 or in a shell surrounding it. This residual amounts to less than about 5% of the total mass of the complex.

Since the molecular material constitutes a large fraction, and perhaps a majority, of the matter in Orion, it must be taken into account in any attempt to understand the structure and evolution of the region. As Figure 2 shows, the Orion association provides a striking example of a sequence of subgroups of decreasing age, culminating in a giant molecular complex. Observations to date indicate that the Orion Nebula, which incorporates the youngest members of the association, interacts with the densest parts of the southern complex. This, along with its apparent alignment with the association, makes it seem plausible that the southern complex is the remnant of a larger cloud out of which the association formed.

The most obvious explanation of the velocity gradient which is observed over some 70 parsecs in the southern complex is rotation with an angular frequency of 4.5×10^{-15} s^{-1} (or period of 4×10^7 yr). Clearly this interpretation of the gradient is not unique. One cannot, for example, rule out the possibility that the cloud is collapsing in one direction (possibly along magnetic field lines) with $v \propto r$. We note, however, that a detailed investigation of the material from half a degree south to one degree north of the Kleinmann-Low (KL) nebula shows a velocity and density structure which is most easily explained by the collapse and fragmentation of a rotating cloud (Kutner, Evans, and Tucker 1976). Though this is not conclusive, it appears reasonable to pursue the idea of rotation and consider its possible origins.

It is possible that rotation is present from the time of formation of the cloud. An obvious source of angular momentum is the Galactic differential rotation. The sense of rotation of the southern complex is opposite to that of the Galaxy, contrary to what one usually expects. (See, e.g., Mestel 1966, for a discussion of condensation in a differentially rotating fluid.) However, if the initial condensation is very elongated along a Galactic radius, then its spin will be opposite to that of the Galaxy. There is, however, one serious difficulty with this picture. If the cloud was rotating before the formation of the association, one would expect the radial velocities of the O and B stars to have a gradient in the same sense. Taking the radial velocities of Lesh (1968), this is not the case; in fact, the stars show a slight gradient in the opposite direction. We note that this apparent discrepancy exists for any model in which the gradient exists prior to the formation of the association.

It is of interest to consider the alternative possibility, that the mechanism responsible for the propagation of the star formation might also have produced the observed gradient. Based on the ages and separations of the subgroups (Blaauw 1964), it appears that star formation has proceeded through the cloud at 10–15 km s^{-1}. Taking this velocity and the age of the Id subgroup, one finds that at present the rotation should have progressed some 40 to 60 pc beyond the Orion Nebula, and the cutoff in the gradient at $l^{\mathrm{II}} = 214°$ falls in this range. A number of models have been proposed to explain the propagation of star formation in associations, and recent theoretical investigations have shown that the application of some of these models to the cool large molecular complexes may produce the observed properties. Such models generally fall into two categories: (1) those schemes in which star formation is initiated and propagated via the passage of some large-scale disturbance; and (2) those which depend on some local mechanism. Examples of the large-scale disturbance in the first type are the passage of a density wave (e.g., Woodward 1976) or an expanding supernova remnant. In Orion, another possibility is raised by Weaver's (1974) observation of a flow of gaseous material at about 10 km s^{-1}, associated with the expansion of the Gould Belt system (Lesh 1968) in the direction of Orion. An example of a local mechanism for the propagation of star formation is that proposed by Oort (1954) and recently investigated by Elmegreen and Lada (1977), in which each subgroup is formed by the ionization and shock front from the previous subgroup compressing the cloud.

It is interesting to speculate on how, in general terms, the rotation of the remnant molecular cloud can be fitted into any of the above schemes. Let us consider, for example, the model in which star formation is induced in a cloud passing through the Galactic spiral shock. If the cloud enters the shock obliquely, then it may suffer differential braking, causing rotation.

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However, it can be shown, from simple geometric arguments, that for Orion, a configuration which produces the observed direction of star formation causes the cloud to rotate the wrong way. A flow of material outward from the Galactic center, such as that found by Weaver (1974), could produce the observed sense of rotation and the observed direction of the star formation. If the star formation is propagated by the expansion of a supernova remnant, then one must know the center of expansion to place a constraint on the relationship between the direction of star formation and the sense of rotation. Finally, if the star formation proceeds via local propagation, this may be capable of imparting rotation, if all the stars form on one side of the cloud. It is not clear that such a process could have a significant effect tens of parsecs from the youngest subgroup. Perhaps the magnetic fields in the cloud play an important role in the propagation of the disturbance.

In discussing the origin of the Orion association, it is also interesting to see what the molecular observations can tell us about Barnard's loop. In Menon's (1958) model, the excitation producing the Hα emission from the ring cannot be due to radiation from the early-type stars within the ring, and occurs instead because of heating at the edge of an expanding shell. O'Dell, York, and Henize (1967) propose a model in which most of the neutral hydrogen has been swept up by the expanding shell, allowing a flux of UV photons, sufficient to explain the observed excitation, to reach the shell. The observation that the brightest part of the ring occurs where it crosses L1630 suggests some interaction between the ring and the material in the cloud. While CO maps do not show heating at the points where the molecular complexes cross Barnard's loop, the CO emission falls off noticeably as both clouds cross the ring, and as the southern complex crosses the ring there is a shift in velocity and an end to the velocity gradient.

In the above discussion, we have attempted only to point out some of the questions raised and avenues opened up by the molecular observations. The discussion does, however, point out the great value of velocity information, obtained from CO observations, in studying the structure and evolution of OB associations. It is always possible that observations of one region may be dominated by special circumstances. In order to appreciate the significance of the Orion observations, it will be important to look for similar large-scale velocity structure in the vicinity of other associations.

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