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COUPLING OF THE MAGNETIC FIELD AND ROTATION IN THE DARK CLOUD B5

JUDITH S. YOUNG,[1] WILLIAM D. LANGER,[1,2] PAUL F. GOLDSMITH,[1] AND ROBERT W. WILSON[2]
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ABSTRACT

We present observations which indicate that the central region of the dark cloud B5 is rotating in the opposite sense to that of the bulk of this $\sim 300\ M_{\odot}$ region. The direction of elongation of the cloud coincides with its axis of rotation; both are perpendicular to the galactic plane and to the direction of the magnetic field in the region. This configuration, together with the unusual rotation curve of the cloud, suggests that magnetic braking has played an important role in its dynamical evolution. The retrograde motion of the core relative to the bulk of the cloud is explainable if significant angular momentum transfer has taken place by means of a frozen-in magnetic field.

Subject headings: interstellar: matter — magnetic fields — rotation

I. INTRODUCTION

At the present time, the structure of dark interstellar clouds poses several difficult questions. It does not appear reasonable that all of these objects are in free-fall collapse (Field 1978). However, since their gravitational potential energy greatly exceeds the thermal energy from the kinetic temperature, collapse would be likely to occur. Consequently, other support mechanisms have been sought, and magnetic fields have, in particular, been advanced as the agent impeding collapse. Here, we wish to present the unusual kinematic behavior of the dark cloud B5 which may be relevant to these questions.

The dark cloud B5 is a relatively isolated object situated in a region of irregular optical obscuration located 17° below the galactic plane at a longitude of 160°. The distance of the cloud is estimated to be 160 pc (Young *et al.* 1982). The overall shape of the cloud, as revealed by ^{12}CO mapping, is approximately an ellipse with an axial ratio of 2:1, elongated perpendicular to the galactic plane. The overall physical dimensions of B5 on the sky are 1.5 pc by 3.0 pc. Along seven radial cuts (including the minor axis), the ^{12}CO emisson drops below the 1 K level. In only one direction is the cloud less perfectly isolated in that the ^{12}CO emission falls to $\leq \frac{1}{3}$ of the peak value (Young *et al.* 1982). The magnetic field in the vicinity of the cloud, as determined from polarization measurements (Turnshek, Turnshek, and Craine 1980) is parallel to the galactic plane, and thus coincides with the minor axis of B5.

[1]Five College Radio Astronomy Observatory, Department of Physics and Astronomy, University of Massachusetts.
[2]Crawford Hill Laboratory, Bell Laboratories, Holmdel, New Jersey.

II. OBSERVATIONS AND RESULTS

The ^{13}CO and C^{18}O observations were obtained with the 7 m antenna of Bell Laboratories; the observations of ^{12}CO were made with the 14 m antenna of the Five College Radio Astronomy Observatory. Spectral resolution for ^{12}CO was provided by a 256 channel autocorrelator with velocity resolution of 0.25 km s^{-1}. A spectrum expander provided 0.14 km s^{-1} and 0.07 km s^{-1} resolution for ^{13}CO and C^{18}O, respectively. We have made observations along four diagonal strips through the central position of B5 [$\alpha(1950) = 3^{h}44^{m}28^{s}.7$, $\delta(1950) = 32°44'30''$]. The ^{12}CO spatial-velocity maps show velocity shifts across the cloud which are consistent with rotation about a single axis. It is possible to envisage other explanations for the observed velocity shifts involving waves propagating through the gas, complex shearing motions, etc. However, simple, essentially rigid-body rotation appears to be the most straightforward interpretation. Figure 1 shows the ^{12}CO spatial-velocity map along the northwest-southeast axis of B5, where the largest velocity shifts are seen. From the observations, we infer that the axis of rotation is the elongated axis of B5. The angular momentum vector is antiparallel to that of the rotation of the Galaxy.

A detailed study of B5 (Young *et al.* 1982) indicates that the ^{12}CO $J = 1{-}0$ emission does not appear to reflect the structure deep within the cloud. To investigate the rotation of the interior of the cloud, we have mapped the essentially optically thin C^{18}O $J = 1{-}0$ emission (see Langer *et al.* 1980 and Wilson, Langer, and Goldsmith 1981 for a discussion of the degree of saturation in these lines). The C^{18}O spectra taken along the direction perpendicular to the cloud's axis of rotation (i.e., parallel to the galactic plane) are shown in Figure 2. Within the central 11′ region, the C^{18}O spectra

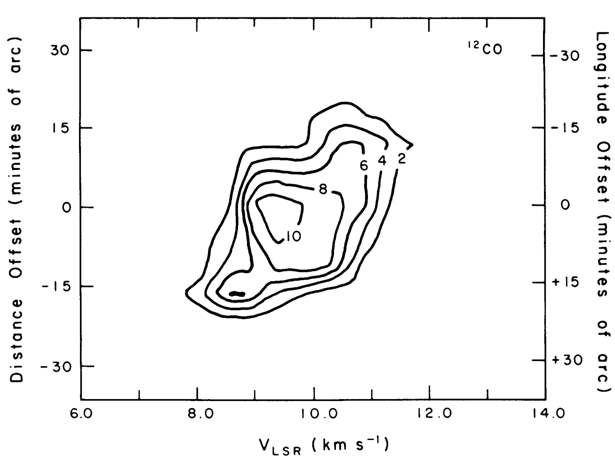

FIG. 1

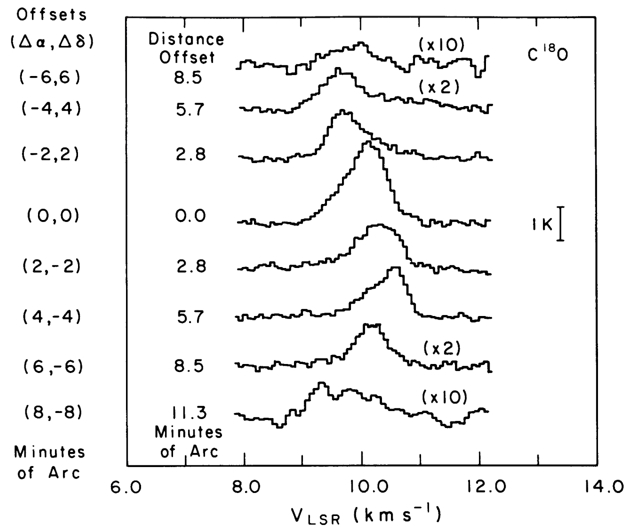

FIG. 2

FIG. 1.—Spatial-velocity map of ^{12}CO emission in B5. The orientation of the strip is essentially in galactic longitude, as indicated by the right-hand scale. The galactic coordinates of the central position are $l = 160°31'$, $b = -16°49'.5$. The strip shown here is perpendicular to the axis of rotation and shows the overall rotation of the cloud with the portions at greater longitude approaching the Earth relative to the regions at smaller longitude. The contours are in units of antenna temperature corrected for atmospheric attenuation and main beam efficiency.

FIG. 2.—$C^{18}O$ emission profiles along the same strip in galactic longitude, with corresponding offsets in right ascension and declination indicated in parentheses. The central 10′ of the cloud show a clearly defined rotation in the opposite sense to that shown by the more extended ^{12}CO emission shown in Fig. 1. Outside of this central region, the velocity gradient changes sign and the velocities rejoin those indicated by the ^{12}CO.

show velocity shifts which can be interpreted as rotation, *but in the opposite sense* to that indicated by the ^{12}CO map.[3] Thus we have the remarkable result that the core of the cloud appears to be in retrograde motion with respect to the bulk of the cloud. Outside this core, the $C^{18}O$ velocity gradient reverses its sense and coincides with that indicated by CO. The $C^{18}O$ lines are too weak to be studied beyond the extreme positions shown in Figure 2, corresponding to a distance of ~ 10′ from the center. Further evidence for a counterrotation of the cloud core is found in the ^{13}CO data shown in Figure 3. The larger widths of the ^{13}CO lines (due to saturation) prevent us from seeing the detailed structure within the core revealed by $C^{18}O$. However, the higher intensities of the ^{13}CO lines permit us to study the structure on a larger scale. Both the rotation of the outer regions of the cloud *and* the counterrotation of the core are indicated by the data of Figure 3.

III. DISCUSSION

The dynamical evolution of a condensation in the interstellar gas is governed by a number of factors, including angular momentum and magnetic fields. To evaluate these effects for B5, we consider the cloud to be composed of a sphere and an ellipsoid, corresponding to the core and to the bulk of the cloud, respectively. The properties of the core are $n(H_2) = 4 \times 10^3$ cm^{-3}, radius = 0.25 pc; while those for the bulk of the cloud are $n(H_2) = 1.7 \times 10^3$ cm^{-3}, semiminor axis = 0.75 pc, semimajor axis = 1.5 pc. The mass of the cloud core is 10 $M_\odot$, while that of the bulk of the cloud is 260 $M_\odot$.[4]

The angular velocity of each component can be calculated from the change in velocity across it; $\omega \approx \Delta v / \Delta l$. From the ^{12}CO data, we determine the angular velocity of the bulk of the cloud to be $\omega_b = -4.2 \times 10^{-14}$ s^{-1}; from $C^{18}O$ data, the angular velocity of the cloud core is found to be $\omega_c = 6.6 \times 10^{-14}$ s^{-1} (posi-

[3]Another explanation for the observed rotation curves is bipolar mass outflow from an embedded object, as seen in the study of L1551 by Snell, Loren, and Plambeck (1980). However, a distinct difference is that the velocity of the peak of the emission does not shift within their maps; rather, it is the line wings which are blueshifted in one direction from the cloud center and redshifted as one maps in the opposite direction. Since our line profile peaks show a systematic shift, it appears unlikely that mass outflow is the correct explanation. The observed changes in the sign of the velocity gradient could also be produced by a line of three rotating regions, with adjacent regions rotating in opposite directions. We reject this model because the ^{12}CO spectra do not show this behavior, indicating that the counterrotation must be confined to the core of the cloud.

[4]The extent of the cloud along the line of sight can be estimated from the CO column density and the assumption of a $C^{18}O$ fractional abundance (in the core) of 1×10^{-7} (Goldsmith *et al.* 1980); this, together with the hydrogen density, enables us to derive a line-of-sight extent of ~ 1.0 pc. Since the $C^{18}O$ abundance falls rapidly 15′ from the center (Young *et al.* 1982), this indicates that B5 is approximately symmetrical about the major axis.

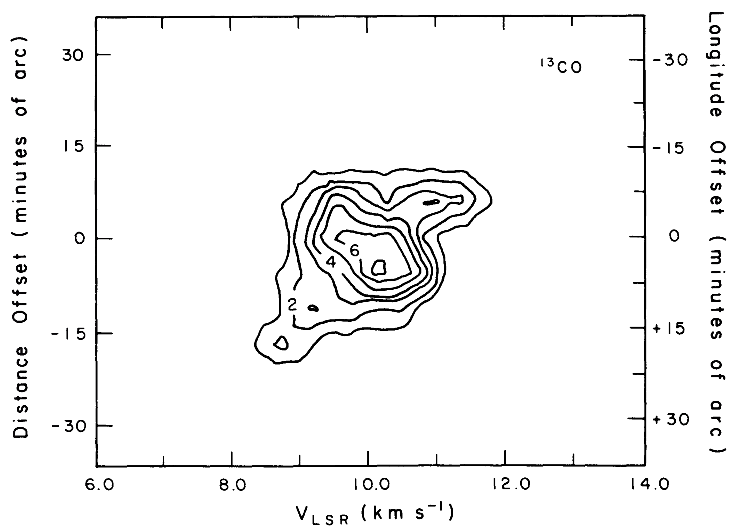

FIG. 3.—Spatial-velocity map of ^{13}CO emission in B5. The contours are in units of antenna temperature corrected for atmospheric attenuation and main beam efficiency. The contours of the 6–4 K emission are elongated perpendicular to those of the more extended, lower-valued emission, indicating that the central portion of the cloud is rotating in the opposite sense of the bulk of the cloud.

tive values indicate angular momentum parallel to that of the Galaxy). The angular momentum of the bulk of the cloud is equal to 5.0×10^{58} g cm^2 s^{-1}, approximately 100 times greater than that of the core, and is opposite to that of the Galaxy.

The kinetic energy of the rotation present in B5 is equal to 1×10^{45} ergs, slightly less than the gravitational potential energy which is approximately 3×10^{45} ergs. Thus, it is reasonable that its evolutionary history is that of a gravitationally bound object. Such a fragment, if initially spherical and rotating, should collapse fastest along the axis aligned with its angular momentum. Eventually, the fragment should evolve to an ellipsoidal shape which is flattened parallel to the rotation axis. Clearly, this is not the case for B5, which, as seen in the ^{12}CO data, has its major axis parallel to its axis of rotation. Some other force must have retarded its collapse in this direction, and we suggest that the agent is the magnetic field, aligned perpendicular to the axis of rotation. This requirement agrees with the direction of $\vec{B}$ determined from several stars less than a degree away (Turnshek, Turnshek, and Craine 1980).

The outstanding problem remaining is the velocity field within the cloud. While a precise analysis of the dynamical evolution of a collapsing, rotating fragment containing magnetic fields has not been made, simplified versions of this problem which can explain the rotation curve found for B5 have been solved analytically by Mouschovias and Paleologou (1979, hereafter MP) and Gillis, Mestel, and Paris (1979, hereafter GMP). MP consider a cylindrical cloud (or fragment) coupled to an external medium by a frozen-in magnetic field; both components have uniform, but different, densities. The analysis of GMP treats a spherical core, coupled to an envelope, which is itself coupled to an external medium with a frozen in magnetic field; the inner- and outermost zones have constant, but different, densities, while three density laws are considered for the intermediate zone. These authors solve the equations of the cloud and the surrounding material with the cloud given an initial angular velocity perpendicular to the magnetic field. The inner component transfers angular momentum to the external region and slows down (magnetic braking). The types of motion that are possible depend on the density contrast between the cloud (or fragment) and its surroundings. At the point where the cloud (or fragment) has transferred its angular momentum to the external medium, their relative angular positions are such that the external medium is exerting a restoring torque on the cloud. As a result, the cloud reverses the sense of its rotation.

In the model of MP the core and bulk of B5 can be identified with their "cloud" and "external medium," respectively. The actual dynamics of B5 are more complicated because of the presence of a third component—the intercloud medium—and thus the treatment of GMP corresponds more closely to the structure of B5. The likely transfer of angular momentum is from the core to the bulk of the cloud, and the angular momentum of the bulk can be transferred to the intercloud medium. As we are concerned only with the reversal of the core's motion, the influence of the intercloud medium can be neglected and the model of MP can be used along with that of GMP. Magnetic braking and the reversal of the core's motion can occur only if the cloud does not rotate uniformly. The collapse of a rotating cloud and the formation of a density gradient will cause the core to spin faster than the outer part. This speedup corresponds to the impulse given to the cloud component in the models of MP and GMP. Since the density contrast between the core and the bulk is a factor of ≤ 10, only one reversal of velocity occurs (see, e.g., Figs. 2*b* and 4*c* in MP). This implies that the characteristic time scale for magnetic braking is 2×10^5 years and that the present moment corresponds to $\sim 6 \times 10^5$ years after the onset of magnetic braking for the core. The present value of the free-fall collapse time for the bulk of the cloud is 7×10^5 years. Allowing for the retardation by the magnetic field and rotation, the substantial increase in density of the cloud compared to plausible initial conditions indicates an age considerably in excess of this. Since in this picture the core has reversed its direction of rotation while the bulk has not, we must conclude that the entire cloud was initially formed having retrograde rotation with respect to the Galaxy.

Alternatively, the cloud core may have decoupled from the magnetic field at a relatively early phase in its evolution and thus still has the original sense of rotation of the B5 cloud. In this case, the envelope is the region which has undergone a velocity reversal due to magnetic braking. This scenario is relatively close to the analysis of MP in that the bulk of the cloud is not too far from cylindrical, has approximately uniform density, and the core can be ignored as it is magnetically decoupled. The density contrast between the bulk of B5 and the surrounding medium is not known, but if a factor of 100 is adopted, the maximum reverse angular velocity occurs for $t = 10^6$ yr (from Fig. 2*a* of MP). Of course, in reality there may be a gradual decline in density outside the edge of the cloud, so the time scales are only approximate.

In conclusion, it appears that the shape and orientation of B5, together with the unusual velocity curve we have observed, suggest that angular momentum transfer by a frozen-in magnetic field, and magnetic braking, have played an important role in the evolution of this dark cloud. The apparent counterrotation of the core with respect to the bulk of the cloud indicates that either the inner or the outer portion of B5 has reversed its sense of rotation during the evolution of the cloud. Calculations of a realistic rotating magnetized cloud, allowing for the possible decoupling of the field, viscosity, and collapse due to gravity, are required for detailed as well as statistical comparison of observations with theory. Our observations together with those reported previously (Clark and Johnson 1981) indicate that magnetic braking may have general importance for the dissipation of angular momentum required for star formation.

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Paul F. Goldsmith and Judith S. Young: Five College Radio Astronomy Observatory, Department of Physics and Astronomy, University of Massachusetts, Amherst, MA 01003

William D. Langer: Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ 08544

Robert W. Wilson: Crawford Hill Laboratory, Bell Laboratories, Holmdel, NJ 07733