THE ASTROPHYSICAL JOURNAL, 245:898–902, 1981 May 1

A TURBULENT ORIGIN FOR THE ROTATION OF MOLECULAR CLOUDS[1]

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Received 1980 May 15; accepted 1980 November 12

ABSTRACT

The observed rotational properties of dark clouds are shown to be consistent with the turbulent character of the interstellar medium. The turbulent flow is easily maintained by the shearing action of differential galactic rotation. The size distribution of molecular clouds inferred from observations is found to closely resemble a Kolmogorov turbulent spectrum. These findings suggest that the processes leading to the formation and evolution of such clouds may depend strongly on the properties and characteristics of interstellar turbulence.

Subject headings: interstellar: matter — interstellar: molecules — stars: formation — turbulence

I. INTRODUCTION

Spectroscopic observations of molecules in dark clouds have revealed several clouds to be rotating faster than the Galaxy (see Table 1). This rotation is generally interpreted as being the result of angular momentum conservation during cloud collapse from an initial state of corotation with the Galaxy. For such clouds, the angular velocity ω is expected to scale like

$$\omega/\omega_G = (R_0/R)^2 = (n/n_0)^{2/3} , \qquad (1)$$

where ω_G ($= 8 \times 10^{-16}$ s^{-1} in the solar neighborhood) denotes the angular velocity of the Galaxy, and R is the radius of a spherical cloud with an average particle density n (subscripts denote initial values corresponding to $\omega = \omega_G$). Each cloud surveyed in Table 1 has an average particle density in the range $n \approx 10^3$–10^4 cm^{-3} so that clouds of small spatial dimension are generally those of small mass. If n_0 is interpreted as the critical density for gravitational collapse, we expect from general stability analyses (e.g., the Jeans criterion for the gravitational instability of a cloud of mass m; viz. $m/m_\odot \gtrsim 10[T^3/n_0]^{1/2}$) that, in general, low-mass clouds form in regions of relatively high n_0 and, according to equation (1), should therefore rotate slower than the large (high-mass) clouds. However, the observations seem to indicate just the contrary: the smaller clouds are generally the fastest rotators. Furthermore, if stars and stellar systems acquired their angular momenta directly from galactic rotation, angular momentum vectors would then generally be aligned perpendicular to the galactic plane, contrary to the observed (1) random orientation of rotational axes of early-type stars (Huang and Struve 1954) and field Ap stars (Abt, Chaffee, and Suffolk 1972), (2) lack of dependence of inclinations in visual binary systems on galactic latitude (Finsen 1933), and (3) lack of evidence for a preferred galactic distribution of the orientations of the orbital planes of eclipsing binaries (Huang and Wade 1966; Rudy 1979). The general alignment of elongated dark clouds parallel to the galactic plane (Hopper and Disney 1974; Disney and Hopper 1975) is probably not a rotation effect (Heiles and Katz 1976), and the observations of Sanders and Solomon (1977) indicate no preferred alignment for elongated giant molecular clouds in the interior of the Galaxy. The rotating clouds in Table 1 exhibit no strong perference for alignment with respect to the galactic plane. It is perhaps noteworthy that our solar system is inclined to the galactic plane by some 60°.

Cloud rotation may be braked by the action of frozen-in magnetic fields (see Mouschovias 1978 for a review). For efficient braking, the time scale for angular momentum disposal $t_J \approx 8 \times 10^5$ $(T/20\text{ K})^{1/2}$ yr, where T is the cloud temperature (Mouschovias 1979), must not exceed the magnetic diffusion time

$$t_D \approx 2 \times 10^6 \, [1 + (\kappa/4.5 \times 10^{-8})] \text{ yr}$$

for a magnetically supported dust cloud with fractional ionization κ (Elmegreen 1979). For cool dark clouds, $t_J < t_D$ so that such clouds should rotate synchronously with the Galaxy, contrary to the observations presented here in Table 1. Although magnetic braking may be significant for some clouds (in particular, diffuse H I clouds [see Field 1978]), its efficiency is evidently diminished for many compact dark clouds.

If centrifugal forces become comparable to gravitational forces, the collapse of a rotating cloud will be halted, at least in the two spatial dimensions perpendicular to the rotation axis. For a uniform, spherical, rigidly rotating cloud, the condition for rotational "stability" at

[1] This work was supported in part by the National Science Foundation under grant AST 76-80200-A01, in part by the Research Corporation, and in part by a grant from NASA administered by the American Astronomical Society.

TABLE 1

OBSERVATIONS OF ROTATING CLOUDS

Source	Observed Line-of-Sight Velocity Gradient ($km\ s^{-1}\ pc^{-1}$)	R(pc)	ω/ω_G[a]	θ_{ω,ω_G}[b]	Reference
1. Orion					
a. L1641	0.13	33.0	6.7	180	Kutner *et al.* 1977
b. outer KL	1.37	2.1	70	150	Linke & Wannier 1974
c. inner KL	5.7	0.22	300	120	Harvey *et al.* 1974
2. ρ Oph	0.5	1.2	8.5	90	Myers & Ho 1975
3. Taurus	0.24	4.2	13	40	Crutcher 1973
4. L1640	0.6	1.2	18	150	Kislyakov & Turner 1976
5. L134	0.67	0.62	18	50	Brooks *et al.* 1976
6. NGC 7129	0.40	1.5	22	45	Loren 1977*b*
7. Mon R2	0.43	1.8	22	90	Loren 1977*a*
8. CRL 437	0.23	1.0	24	90	Schneps *et al.* 1978
(core)	2.1	0.33	100	90	Schneps *et al.* 1978
9. B361	1.26	0.76	64	90	This paper
(core)	0.61	0.20	64	90	This paper
10. B163	1.9	0.32	94	180	Martin & Barrett 1978
11. B68	2.1	0.12	110	90	Martin & Barrett 1978
12. B163 SW	3.0	0.25	160	180	Martin & Barrett 1978
13. B213 NW	5.8	0.08	300	90	Clark & Johnson 1978

[a] Assuming a random inclination i of rotation axis to line of sight, for which $\langle \sin i \rangle = \pi/4$ (Allen 1973, p. 210).

[b] The apparent approximate angle (in degrees) between the angular momentum vectors of the cloud and the Galaxy, as seen on the plane of the sky.

the centrifugal limit becomes $\omega \approx (4\pi G\bar{\rho}/3)^{1/2}$ where $\bar{\rho}$ is the average mass density within a cloud and G is the gravitational constant. Thus, a sample of clouds such as that presented here in Table 1, with $\bar{\rho}$ not very different from cloud to cloud, should exhibit rotation at approximately the same ω if such clouds rotate at the centrifugal limit. Inspection of Table 1 shows that this does not appear to be the case, and we conclude that, at least for most of these clouds, ω is not determined by centrifugal balance. However, this conclusion must be regarded as tentative since many clouds are not uniform, nor are they spherical or rigidly rotating. Even so, this finding suggests that a "virial" mass, which is derived assuming rotation at the centrifugal limit, may greatly underestimate the actual mass of a cloud. We point out that all seven dark clouds surveyed by Dickman (1976) rotate (if at all) well below the centrifugal limit. Other difficulties with rotationally supported clouds are discussed by Field (1978).

The turbulent nature of the interstellar medium has been well established (see, e.g., Kaplan 1966). We know from studies of hydromagnetic turbulence that vorticity is larger in the smaller eddies (Batchelor 1953; Landau and Lifshitz 1959). Observations of rotating clouds (Table 1) indicate a gradual increase in ω for the smaller clouds, suggesting that the rotation (a manifestation of vorticity) of these clouds may be established by the turbulent flow in the interstellar medium. Indeed, some time ago Hoyle (1945) and McCrea (1960, 1961) suggested that condensation and star formation may take place in regions where the local turbulence is abnormally small, thus avoiding the classical "angular momentum problem" in star formation. A turbulent origin for the angular momentum of protostars has the attractive feature of explaining the random orientation of angular momentum vectors for stars and stellar systems.

This paper examines the hypothesis that cloud rotation is determined by the turbulent character of the interstellar medium. In § II we derive an equation for the vorticity ($\sim \omega$) in a fully developed turbulent flow and compare this result with the observations of cloud rotation. Implications of a turbulent origin for the rotation of dark clouds, particularly regarding the size distribution and mass spectrum of molecular clouds, are discussed in § III. The main conclusions of this paper are summarized in § IV.

II. TURBULENCE AND CLOUD ROTATION

Turbulent flow may be regarded as a superposition of turbulent eddies of various sizes, from the largest l, a characteristic length which gives the size of the region in which the turbulent flow originates, to the smallest λ_0, the length scale at which viscosity and the energy dissipation which it entails becomes important. According to the theory of fully developed subsonic turbulence (Landau and Lifshitz 1959), the velocity associated with an eddy of size λ is related to that associated with the largest eddy by the relationship

$$v \approx v_l(\lambda/l)^{1/3}\ , \tag{2}$$

provided Kolmogorov's law applies.[2] We consider a

[2] A number of fluctuations in the interstellar medium appear to be given by power-law spectra, in fact, by chance or otherwise, close to a Kolmogorov spectrum (Kaplan 1966; Lee and Jokipii 1976; Larson 1979, 1980). Although the motions in molecular clouds are supersonic and very little is known about supersonic turbulence, similarities with subsonic turbulence evidently exist.

cloud to be a turbulent eddy of size $\lambda = 2R$. The rotation of a cloud at an angular velocity ω will then be a measure of the vorticity in the turbulent velocity field. The equation for the vorticity is obtained upon dividing equation (2) by the cloud radius, yielding

$$\omega \approx v_l \left(\frac{2}{lR^2} \right)^{1/3} . \tag{3}$$

It remains to determine the basic scale l and the associated velocity v_l.

The basic scale is determined by the source of the turbulence. Because of the severe energy requirements for the maintenance of turbulence throughout the Galaxy, a likely source would seem to be the transverse velocity shear resulting from the differential rotation of the Galaxy (Goldreich and Lynden-Bell 1965). The local shear is

$$-\frac{\Delta v}{\Delta r} = (A - B) + (A + B) = 2A = 30 \text{ km s}^{-1} \text{ kpc}^{-1} , \tag{4}$$

for the Oort constants $A = 15$ km s^{-1} kpc^{-1} and $B = -10$ km s^{-1} kpc^{-1}. A velocity shear of 30 km s^{-1} kpc^{-1} in the solar neighborhood is consistent with the transverse velocity of the interstellar medium inferred from data on the interstellar scintillations of pulsars (Lee and Jokipii 1976). The basic length and velocity scales are related to this shear in a manner

$$-\frac{\Delta v}{\Delta r} \approx \frac{v_l}{l} . \tag{5}$$

Spectroscopic observations of modest-size molecular clouds seem to indicate a turbulent velocity of 2 km s^{-1} (e.g., Leung and Brown 1977). The internal velocity dispersion of 21 cm emission features in the interstellar medium, as well as the widths of interstellar calcium K-line absorption components, also correspond to a value of about 2 km s^{-1} (see Spitzer 1968, p. 41). Herbig (1978; see also Jones and Herbig 1979) points out that T Tauri stars typically have motions of the same magnitude (1–3 km s^{-1}), probably as a consequence of formation in the turbulent cloudy component of the interstellar medium. These observations suggest an associated velocity $v_l \approx 3$ km s^{-1}. Combining equations (4) and (5), the basic scale is $l \approx 100$ pc. Indeed, direct observations of a variety of processes, such as brightness fluctuations of starlight (Ambarzumian and Gordeladse 1938; Chandrasekhar and Münch 1952), variations in the polarization of starlight (Jokipii, Lerche, and Schommer 1969), cosmic-ray transport (Jokipii and Parker 1969), fluctuations in Faraday rotation and pulsar dispersion measures (Jokipii and Lerche 1969), and fluctuations in the extinction of planetary nebulae (Lerche and Milne 1980) indicate a correlation length of order ~ 100 pc. The characteristic scale for interstellar turbulence estimated by Kaplan (1966) from Adams's (1949) observations of the interstellar calcium K line is found to be in the range 60–70 pc. That the ratio v_l/l obtained from the interstellar K-line observations so closely matches the value given for $\Delta v/\Delta r$ in equation (4) must be interpreted as strong evidence that turbulent flow in the interstellar medium may indeed originate from the action of differential galactic rotation. By chance or otherwise, the basic scale of interstellar turbulence is comparable to the size of the largest molecular clouds ($\sim$ 100 pc according to Sanders and Solomon 1977).

The lifetime of the turbulent flow can be estimated from the rate of energy dissipation via mode decay of the eddies, which is (Batchelor 1953) $\dot{\epsilon} \approx \frac{1}{2} v_l^3 / l = 4 \times 10^{-5}$ ergs g^{-1} s^{-1}. The shear produced by differential galactic rotation supplies energy at this rate since there is no significant viscous dissipation in the spectral range $\lambda_0 \lesssim \lambda \lesssim l$. The total specific energy available in galactic rotation is $\epsilon_G \approx \frac{1}{2} v_\odot^2 = 3 \times 10^{14}$ ergs g^{-1}, where $v_\odot = 250$ km s^{-1} is the circular velocity of the Sun about the center of the Galaxy. Thus, the lifetime of interstellar turbulence is $\sim \epsilon_G / \dot{\epsilon} \approx 2 \times 10^{11}$ yr, much longer than the estimated age of the Galaxy. The survival time of an *individual* eddy ($\sim \lambda/v \approx 3 \times 10^7$ yr for the largest eddies) is irrelevant when there is a continuous source of energy (Fleck 1980, 1981*a*).

An estimate of the turbulent vorticity in the interstellar medium can now be made using equation (3) and the values for l and v_l determined above. The result is plotted as a solid line in Figure 1 and can be compared to the observations of the rotating clouds in Table 1. The general agreement in magnitude *and* slope $(-\frac{2}{3})$ suggests a turbulent origin for the rotation of these clouds. Observations of rotation within the Orion complex (1a, 1b, 1c) and within the dark clouds CRL 437 (8) and B361 (9) may indicate a small departure from the turbulent spectrum inside these clouds, possibly as a result of gravitational contraction. However, for Orion

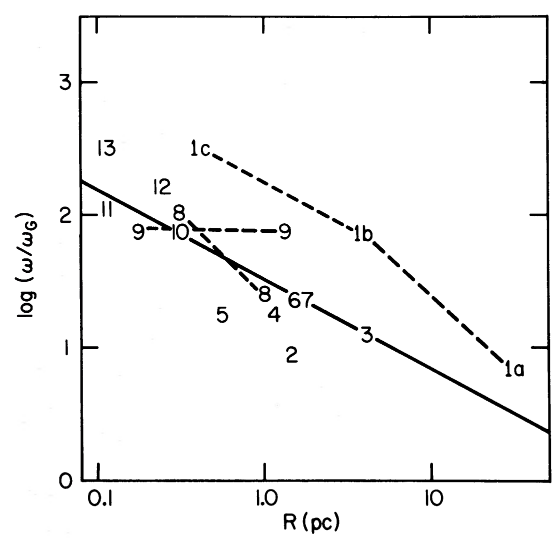

FIG. 1.—A comparison of turbulent vorticity in the interstellar medium (*solid line*; calculated from eq. [3]) and observations of rotating clouds (numbered in Table 1). The dashed lines relate core rotation to the rotation observed in the peripheral region for the three clouds Orion (1), CRL 437 (8), and B361 (9).

and CRL 437 the rotation at the periphery is consistent with a turbulent origin. The data listed in Table 1 for B361 were obtained using the 2 and 6 cm spectral lines of interstellar formaldehyde and dual channel cooled parametric amplifiers on the 43 m antenna of the National Radio Astronomy Observatory[3] between 1976 and 1979. These data will be reported in more detail by Clark and Johnson (1981).

Dickman (1976) has established an upper limit of $\omega/\omega_G \lesssim 72$ for the rotation of seven small ($R \approx 0.5$ pc) dust clouds. The absence of a systematic velocity shift in the molecular cloud NGC 1333 ($R \approx 1.5$ pc) implies $\omega/\omega_G \lesssim 17$ for this cloud (Lada *et al.* 1974). These upper limits are consistent with the turbulent vorticity predicted by equation (3). Due to the stochastic nature of turbulence, some scatter in ω/ω_G for a particular scale size is to be expected. We note also that equation (2) predicts smaller turbulent velocities at smaller scales ($v \sim \lambda^{1/3}$) in agreement with the inferred turbulent contribution to the observed line widths in molecular clouds.

As this paper was being prepared, we became aware of related work by Larson (1979, 1980). He has shown that the internal velocity dispersion (primarily due to the smaller scale motions responsible for the line width) for many molecular clouds and condensations is well correlated with the size and mass of each region. Furthermore, Larson finds that the dependence of velocity dispersion on region size is similar to the Kolmogorov law. Together with our present investigation of large-scale velocity variations across a cloud (i.e., rotation), this would seem to imply that the observed motions in molecular clouds are all part of a common hierarchy of interstellar turbulence.

III. SIZE DISTRIBUTION AND MASS SPECTRUM OF MOLECULAR CLOUDS

In the previous section we have shown that the rotation of molecular clouds may originate from the turbulent flow in the interstellar medium. For a Kolmogorov spectrum, the size distribution of eddies having dimension λ is (Kuiper 1951; Fleck 1981*b*)

$$N(\lambda)d\lambda \sim \lambda^{-1}d\lambda\,, \tag{6}$$

where $N(\lambda)d\lambda$ is the number of eddies (i.e., clouds) with sizes between $\lambda \rightarrow \lambda + d\lambda$. The observed distribution of cloud length (Fig. 2) has been obtained from a sample of 38 clouds identified in a CO survey conducted by Solomon, Sanders, and Scoville (1979). The solid line in Figure 2 has a slope of -1 and thus represents the Kolmogorov spectrum given by equation (6). Due to the sample size, the data point corresponding to the two clouds having $\lambda \approx 100$ pc is statistically rather insignificant. Thus, the agreement with a Kolmogorov eddy spectrum is good. We conclude that the size distribution of molecular clouds may be determined, to a greater or lesser extent, by the turbulent flow in the interstellar medium, in which case the processes leading to the

[3] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the NSF.

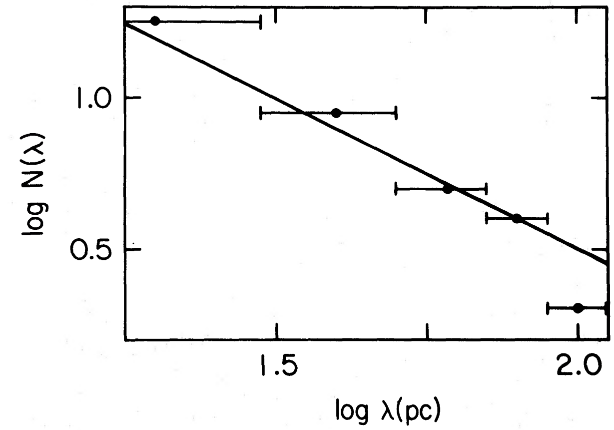

FIG. 2.—The size distribution of molecular clouds. Filled circles indicate the observed distribution of cloud length (error bars denote the range of cloud sizes included in each necessarily discrete counting interval). The solid line has a slope of -1 and represents a Kolmogorov spectrum.

formation and evolution of such clouds are expected to depend on the properties and characteristics of this turbulent flow (see also Fleck 1980, 1981*a*, *b*).

Equation (6) predicts a cloud mass spectrum of the form

$$N(m)dm \sim m^{-1}dm\,, \tag{7}$$

since the average particle density ($\langle n \rangle \approx 10^3$ cm^{-3}) is nearly the same for these clouds. This differs from the somewhat steeper spectrum $N(m) \sim m^{-1.5}$ observed for *diffuse* H I clouds (Penston *et al.* 1969) and predicted by a coagulation theory whereby cloud growth is controlled by inelastic cloud-cloud collisions (Field and Saslaw 1965; Penston *et al.* 1969; Kwan 1979). Kwan's application of coagulation theory to *molecular* clouds has already been criticized by others (e.g., Blitz and Shu 1980; Larson 1980). A discussion of the possible influence of turbulent velocity fields on the mass spectra of diffuse and molecular clouds is given in a separate paper (Fleck 1981*b*).

IV. CONCLUSIONS

The main conclusions to be drawn from this investigation can be summarized as follows:

1. The rotational properties of dark clouds appear to be determined primarily by the turbulent character of the interstellar medium. Centrifugal, magnetic, and angular momentum effects would therefore be insignificant for most clouds.

2. Differential galactic rotation is sufficient to maintain the turbulent flow in the interstellar medium.

3. The size distribution of molecular clouds in the Galaxy resembles the Kolmogorov turbulent spectrum. Hence, the processes leading to the formation, maintenance, and eventual disruption of such clouds are expected to depend on the properties and characteristics of interstellar turbulence.

4. Since stars form in the cloudy component of the interstellar medium, star formation is likely to be a

stochastic process (e.g., Hunter 1979). The role of turbulence in the star formation process would therefore be important. The random orientation of angular momentum vectors for stars and stellar systems may be relevant here.

We gratefully acknowledge support of this research by NSF under grant AST 76-80200 and the Research Corporation. Partial support was provided by a grant from NASA administered by the American Astronomical Society.

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