Pergamon

Adv. Space Res. Vol. 17, No. 4/5, pp. (4/5)197–(4/5)200, 1996

0273–1177/96 $9.50 + 0.00

0273–1177(95)00567–6

CORONAL X-RAY JETS OBSERVED WITH YOHKOH/SXT

K. Shibata,* T. Yokoyama* and M. Shimojo**

** National Astronomical Observatory, Mitaka, Tokyo 181, Japan*
*** Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-12, Japan*

ABSTRACT

The soft X-ray telescope (SXT) aboard *Yohkoh* has discovered *coronal X-ray jets* associated with small flares in X-ray bright points (XBPs), emerging flux regions (EFRs), or active regions (ARs). The common observed characteristics of these jets are discussed mainly from morphological points of view. It is suggested that magnetic reconnection between emerging magnetic flux and the overlying coronal/chromospheric magnetic field is a key physical process for producing these jets.

INTRODUCTION

Yohkoh/SXT has revealed that *X-ray corona is much more dynamic than had been expected.* Among various newly discovered dynamic phenomena, one of the most surprising findings is the discovery of *coronal X-ray jets* /1/. Here X-ray jets are defined as transitory X-ray enhancements with an apparent collimated motion. In many cases, jets are associated with small flares at their footpoints, and seem to be physically similar to *transient loop brightenings* /2/.

In this short report, we will summarize observed characteristics of X-ray jets, and briefly discuss the magnetic reconnection model for these jets.

OBSERVED CHARACTERISTICS OF X-RAY JETS

We found the following characteristics of jets /1,3-6/:

Frequency and Association with Flares

The number of X-ray jets observed in full frame images (FFI) is more than 10–20 jets per month (during Nov. 91 – Apr. 92). Shimojo /5,6/ compiled a list of 136 jets occurred between Nov. 1, 1991 and Apr. 30, 1992. Almost all X-ray jets except for limb events are associated with small flares (or loop brightenings) in XBPs, EFRs, and ARs. These flares correspond to microflares – subflares or C-class flares. Jets occur nearly simultaneously with flares within a few minutes. The jets tend to recur at the same place.

Physical Conditions

The length of the jets ranges from 1×10^4 km to 4×10^5 km, and the average length is $\approx 1.7 \times 10^5$ km. The (apparent) translational velocity is $\approx 10 - 400$ km/s in most cases, though a few exceeded 1000 km/s, and the average velocity $\approx$ 193 km/s /5,6/. Although it is not easy to measure the temperature of the jets, the SXT filter response property suggests that $T_{jet} \approx 2 \times 10^6 - 10^7$ K and the electron density of the jets $\approx 3 \times 10^8 - 3 \times 10^9$ cm^{-3} /1,4/. From this, we can estimate the mass of the jets $\approx 10^{12} - 10^{14}$ g, and the kinetic energy $\approx 10^{26} - 10^{28}$ erg.

XBP-Jets

Many small or thin jets are ejected from XBPs in coronal holes or quiet regions. Similar jets occur also from XBP-like structures in active regions. The XBPs are usually not resolved well (see

Formation of giant molecular clouds and helical magnetic fields by the Parker instability

Kazunari Shibata*† & Ryoji Matsumoto‡

* Department of Physics and Astronomy, Aichi University of Education, Kariya, Aichi 448, Japan
‡ College of Arts and Sciences, Chiba University, Chiba 260, Japan

† Present address: Solar Physics Division, National Astronomical Observatory, Mitaka, Tokyo 181, Japan.

USING the Nagoya telescope[1], Uchida *et al.*[2] found an unusual helical filamentary structure, spinning about its long axis, in the L1641 cloud in the Orion cloud complex. Noting that this structure is consistent with a helically twisted magnetic field inferred from optical polarization observations[3,4], they argued that the helical filament is a manifestation of torsional magnetohydrodynamic (Alfvén) waves draining angular momentum from a nearby massive cloud, thus promoting collapse and star formation. Here we present an alternative interpretation. We suggest that the Orion molecular cloud complex formed through the Parker instability[5] (the buoyancy of a magnetic field entrained in matter), and that the helical filament is the result of spinning gas falling along the magnetic field and twisting it. The twisted magnetic field, unlike a purely planar field, suppresses the Parker instability on small scales, allowing the generation of finite clouds rather than general turbulence.

The Parker instability[5] is a magnetohydrodynamic instability which occurs if a gas layer in a gravitational field is supported in part by horizontal magnetic fields. Suppose that magnetic field lines are disturbed and begin to undulate. The mass in the raised portion of a loop drains down along the field lines so that the loop top becomes lighter than the ambient medium. If the buoyancy at the loop top is larger than the restoring magnetic tension, the loop rises further and the instability sets in. Parker[5] noted that the falling mass accumulates in the magnetic valleys, explaining the formation of interstellar cloud complexes. According to linear analysis[5], the most unstable perturbation wavelength for $\beta = p_{gas}/p_{mag} \approx 1$, where p is pressure, is $\lambda_{max} \approx 14H \approx 1.4(H/100\,\mathrm{pc})$ kpc, with a growth time of $\tau_{Parker} \approx (2\text{-}5) \times (H/V_A) \approx (2\text{-}5) \times 10^7 (H/100\,\mathrm{pc})\ (V_A/10\,\mathrm{km\,s^{-1}})^{-1}$ years. Here, H is the scale height of the galactic disk, $V_A = B/(4\pi\rho)^{1/2} \approx 10(B/3\,\mu\mathrm{G})\ (n/1\,\mathrm{cm^{-3}})^{-1/2}\,\mathrm{km\,s^{-1}}$ is the Alfvén speed, and n is the number density of atomic hydrogen. The mass, M, of the condensed gas clouds is $M \approx 7 \times 10^5 (H/100\,\mathrm{pc})^3 (n/1\,\mathrm{cm^{-3}})\ M_\odot$.

Since the pioneering work by Parker, workers have continued to develop the linear theory of the Parker instability[6-8], and its application to the formation of intestellar cloud complexes[9,10]. The pure Parker instability (without self-gravity) has, however, been criticized as leading to chaotic structures and turbulence rather than coherent cloud complexes[7,11]. This is because in three dimensions the most unstable mode is that with $k_\perp = \infty$, where $k_\perp$ is the wavenumber perpendicular to the magnetic fields[5]. Elmegreen[7] pointed out that this difficulty is resolved by considering the effect of the self-gravity (the Parker–Jeans instability). We suggest another way to resolve this difficulty: if the magnetic field is sheared or twisted, the short-wavelength 'flute' mode ($k_\perp = \infty$) is stabilized or at least its growth rate is greatly reduced, so that a large-scale flux tube structure with finite $k_\perp$ is created. It is known that dynamo action usually produces a twisted field[12]. Here we give an example of another mechanism for creating a twisted magnetic field.

Matsumoto *et al.*[13] performed a self-consistent, two-dimensional, nonlinear numerical simulation of the Parker instability and found that (1) the maximum velocity of the flow down the loop is comparable to the initial Alfvén speed, (2) shock waves are generated at the foot of the loop if $\beta(t=0) < 3$, whereas a nonlinear oscillation is excited if $\beta(t=0) > 3$, and (3) when $\beta < 3$, a quasi-static dense cloud, corresponding to a giant molecular cloud complex, is formed just below the shock front (Fig. 1). More recently, Matsumoto *et al.*[14] showed that even when $\beta > 3$, shock waves are generated as a result of the nonlinear mode coupling during the nonlinear magnetic loop oscillations, and that a quasi-static cloud is eventually created. Hence, these nonlinear results[13-15] suggest that if giant molecular cloud complexes are created by the Parker instability, there should be a pair of shock fronts just above (or below) the cloud complexes (Fig. 1). In the regions just behind the shocks there may be efficient formation of molecular clouds and stars, similar to those behind the galactic spiral shock waves[16].

Figure 2 shows a map of the molecular clouds in Orion[17]. We note that the distribution pattern of the molecular cloud is similar to the V pattern of the shock fronts found in the nonlinear simulations. The size of the cloud complex (~100-200 pc) roughly agrees with that found in the simulations. Moreover, the magnetic field configuration inferred from the polarization of the star light[3,18] is roughly consistent with that predicted by the simulation. Consequently, we suggest that the Orion molecular cloud complex might have been created by the Parker instability.

There are, however, problems with this hypothesis. First, according to the Parker instability hypothesis, the mass density is maximum inside the V pattern (Fig. 1). However, there is not much mass (in the form of molecular clouds) inside the Orion V pattern. Second, Uchida *et al.*[2] found a prominent helical filamentary structure suggesting the presence of helically twisted

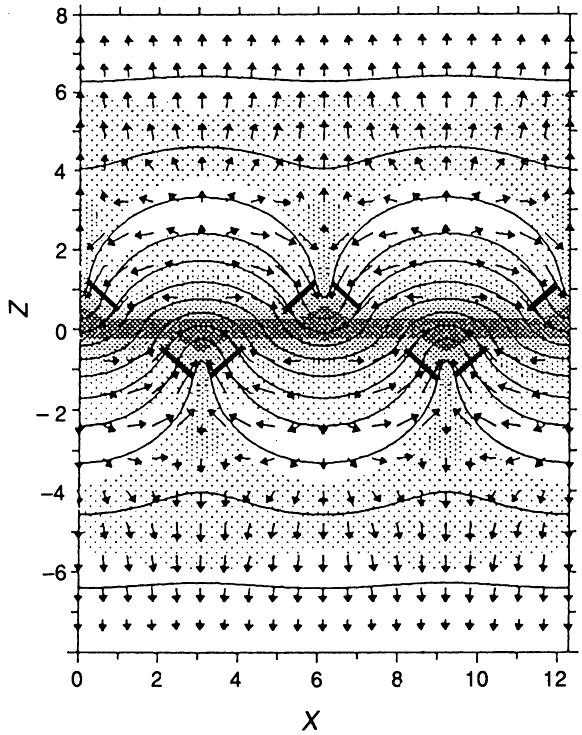

FIG. 1 A typical result of nonlinear simulations of the Parker instability[13]. In this case $\beta = p_{gas}/p_{mag} = 1$ in a later phase ($t/\tau = 8.55$). The magnetic field lines and velocity vectors are shown, and the density is indicated on a logarithmic scale (by the shaded dot pattern). The scale of the velocity vectors is linearly taken such that the maximum velocity in this figure is $2C_s$. The units of length and time are $2.3H$ and $\tau = 2.3H/C_s$, where H is the scale height of the disk and C_s is the isothermal sound speed. The maximum velocity is comparable to the initial Alfvén speed, which is slightly larger than the sound speed. The plane $z = 0$ corresponds to the galactic plane. The thick solid lines, forming V or inverted V patterns, show the positions of the shock fronts produced by the supersonic downflows.

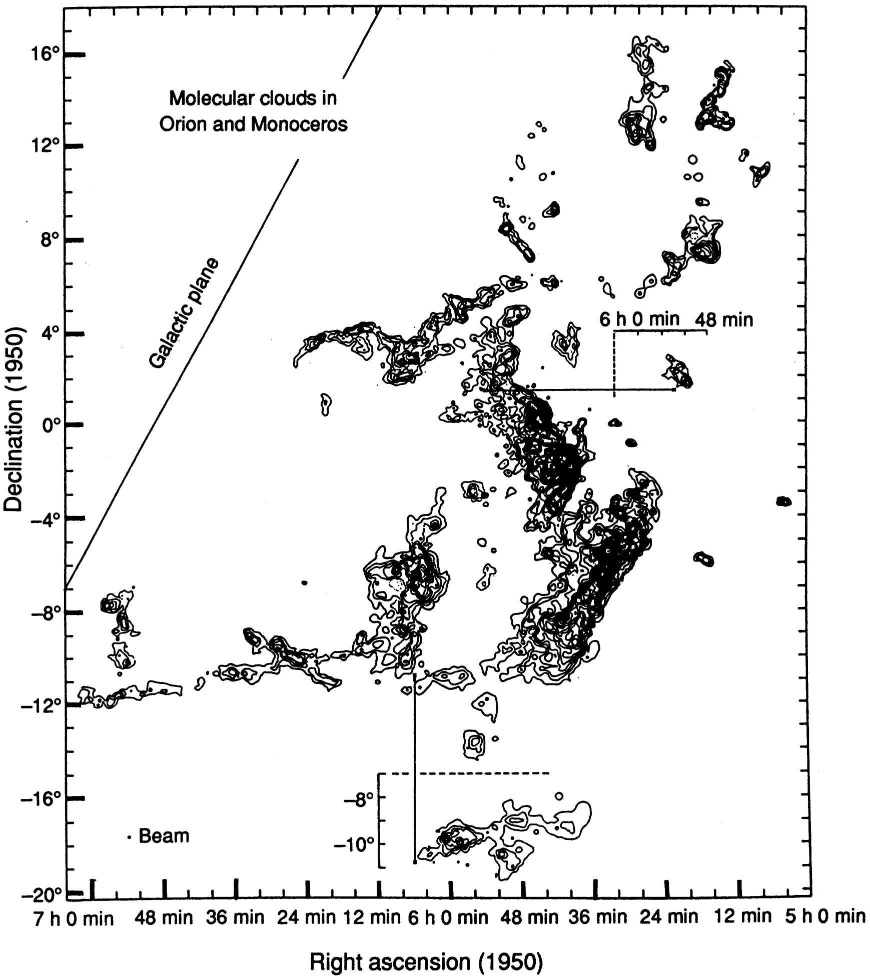

FIG. 2 Contour map of integrated CO emission in the velocity range of -10 to $20\,\mathrm{km\,s^{-1}}$ in Orion and Monoceros, taken from Maddalena *et al.*[17].

magnetic field lines in the Orion molecular cloud complex. Is this newly observed structure consistent with the hypothesis of a Parker instability?

The answer to the second question is yes, as we shall discuss here. We believe (Fig. 3) that magnetic fields in giant molecular clouds can be expected to be helically twisted. These twists exert magnetic pressure, $\nabla(B_\varphi^2/8\pi)$, along the magnetic flux tube[19], supporting the heavy clouds. Hence it is not surprising that there is less mass than expected inside the V pattern; its fall is broken by the magnetic pressure of the twisted field. This may be an answer to the first question. (Note that the common explanation of the cloud distribution pattern in Orion is that the large pressure exerted by the old OB star association on the right pushed the molecular cloud to the left[20]. Our new model may not be inconsistent with this hypothesis, because the V pattern itself could have been primordially produced by our mechanism.)

Nonlinear simulations[13] show that the infalling masses are compressed both by the shock waves and by geometrical effects such as the decreasing cross-sectional area of the flux tube; in fact, the density increases by a factor of 3-10 during the nonlinear stage of the Parker instability. If we consider the effects of additional cooling mechanisms or self-gravity, the infalling masses could be further compressed and finally evolve into a molecular cloud whose density is more than 10^3 times that of the initial gas. During this contraction of the gas, the Coriolis force due to galactic rotation causes the cloud to spin (Fig. 4). This is why magnetic field lines are helically twisted as a result of the Parker instability. Because the sense of the rotation due to the Coriolis force is the same for all contracting clumps of gas in the galactic disk (Fig. 4), the magnetic twists caused by the gas clumps accumulate in the valleys, and also in the upper loops. Note that the whole magnetic valley itself is twisted by the Coriolis force because the average density also grows in the valley. This global twist, however, is not shown in Fig. 4. Consequently we expect that there should be helically twisted flux tubes in all molecular cloud complexes produced by the Parker instability.

To estimate the total angular momentum in the infalling cloud, the angular velocities and other physical quantities, we assume that the infalling cloud is initially described by the following parameters: density $\rho_1 \approx 10^{-24}\,\mathrm{g\,cm^{-3}}$, size $R_1 \approx 100\,\mathrm{pc}$ and angular velocity $\Omega_1 \approx 10^{-15}\,\mathrm{s^{-1}} \approx \Omega_{\mathrm{Galaxy}}(r \approx 10\,\mathrm{kpc})$. Suppose the cloud evolves into a state with density ρ_2, size R_2 and angular velocity Ω_2, as it falls through the shocks and into the magnetic

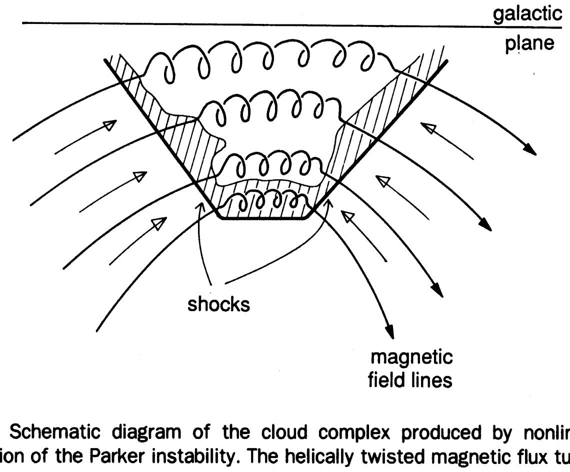

FIG. 3 Schematic diagram of the cloud complex produced by nonlinear evolution of the Parker instability. The helically twisted magnetic flux tubes are generated because of the Coriolis force, and these accumulate inside the giant molecular clouds. This picture may be compared with the observed CO map of the Orion molecular cloud complex (Fig. 2).

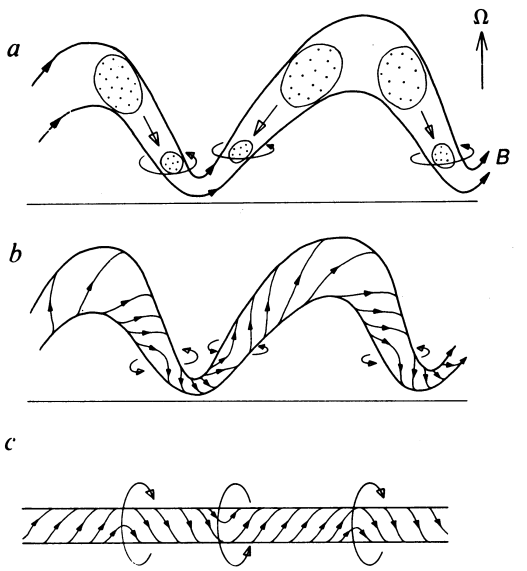

FIG. 4 Schematic diagram showing the origin of the helically twisted magnetic fields. *a*, Before the flux tube is twisted; *b*, after the tube is twisted. Note that the magnetic twist accumulates both in the magnetic field valleys and in the loop tops. *c*, Schematic illustration showing how the tube is twisted. Note that this tube is topologically the same as that shown in *b*.

field valleys. Then the total mass of the infalling cloud is $M_{\rm infall} \approx 10^4 M_\odot$, which is only a fraction of the total mass involved in the cloud complex ($\sim 10^6 M_\odot$). The total angular momentum is $L_{\rm infall} \approx M_{\rm infall} R_1^2 \Omega_1 \approx 10^{63.5}$ g cm^2 s^{-1}. Note that this is much larger than the total angular momentum observed in the helical filament and its base cloud[1] (Y. Uchida, K.S. and R. Rosner, manuscript in preparation), which is $\sim 10^{59}$–10^{60} g cm^2 s^{-1}. The mass conservation law, $R_2^3 \rho_2 \approx R_1^3 \rho_1$, and angular momentum conservation law, $R_2^2 \Omega_2 \approx R_1^2 \Omega_1$, yield $\Omega_2 \approx (R_1/R_2)^2 \Omega_1 \approx (\rho_2/\rho_1)^{2/3} \Omega_1 \approx 10^{-13}$ s^{-1}, if $\rho_2 \approx 10^3 \rho_1 \approx 10^{-21}$ g cm^{-3}. This is much larger than the usual angular velocities of molecular clouds[21], 10^{-15}–10^{-14} s^{-1}. Similarly, the rotational velocity of the cloud becomes $V_{\varphi,2} \approx R_2 \Omega_2 \approx (\rho_2/\rho_1)^{1/3} R_1 \Omega_1 \approx 30$ km s^{-1}, which is much larger than the observed rotational velocities of molecular clouds, $V_\varphi \approx 0.1$–1 km s^{-1}. Consequently, we have to consider the effect of magnetic braking caused by generation of the helical magnetic twists (Fig. 4) to explain the small rotational velocities actually observed.

We shall now estimate the braking time and the degree of magnetic twist. If the Alfvén transit time across a tenuous loop is much shorter than the growth time of the Parker instability, then the braking time can be approximated by $\tau_{\rm braking} \leq \lambda / 2\langle V_{\rm A} \rangle \approx 7 \times 10^7$ yr $\approx$ a factor $\times\, \tau_{\rm Parker}$, where $\langle V_{\rm A} \rangle$ is the average Alfvén speed inside the whole flux tube including the loop and the valley. The ratio of the twisted component, B_φ, to the initial field strength, B_0, becomes

$$\frac{B_\varphi}{B_0} \approx \frac{V_{\varphi,2}}{\langle V_{\rm A} \rangle} \approx 3 \left(\frac{\rho_2/\rho_1}{10^3} \right)^{1/3} \left(\frac{R_1}{100\ \rm pc} \right) \left(\frac{\Omega_1}{10^{-15}\ \rm s^{-1}} \right) \left(\frac{\langle V_{\rm A} \rangle}{10\ \rm km\ s^{-1}} \right)^{-1}$$

Hence the degree of the twist, B_φ / B_0, is of the order of unity, which is comparable to the observed degree of the twist in the helical filaments in the Orion molecular cloud complex[2].

Finally, we note that Beck *et al.*[22] found a three-dimensional, arc-like magnetic field structure extending out of M31 on a scale of ~4.5 kpc, which also fits our model well. This field structure is associated with a large HI cloud complex and with a CO cloud[23] with a strong nonthermal radio source. Hence they suggested that this might be the first Parker–Jeans instability observed in a galaxy other than our own. Another interesting fact about this M31 cloud complex is that the CO intensity is low in its centre (that is, a double-peaked CO feature)[23], similar to the distribution pattern of the molecular clouds in the Orion complex. We suggest that the low CO intensity may correspond to a region with strong, helically twisted magnetic fields (Fig. 3). *Note added in proof*: R. Beck has informed us that the distance between the two peaks in the M31 CO cloud[23] is about 250 pc, which is much smaller than the arc (~4.5 kpc) and is comparable to the distance between the two shocks in our model (Fig. 3). □

Received 21 April; accepted 19 August 1991.

1. Fukui, Y., Iwata, T., Mizuno, A., Bally, J. & Lane, A. in *Protostars and Planets III* (University of Arizona Press, in the press).
2. Uchida, Y. *et al. Nature* **349,** 140–142 (1991).
3. Heiles, C. in *Interstellar Processes* (eds Hollenbach, D. J. & Thronson, H. A.) 171–194 (Reidel, Dordrecht, 1987).
4. Vrba, F., Strom, S. E. & Strom, K. *Astr. J.* **96,** 680–694 (1988).
5. Parker, E. N. *Astrophys. J.* **145,** 811–833 (1966).
6. Shu, F. H. *Astr. Astrophys.* **33,** 55–72 (1974).
7. Elmegreen, B. G. *Astrophys. J.* **253,** 634–654 (1982).
8. Nakamura, H., Hanawa, T. & Nakano, T. *Publs. Astr. Soc. Japan* (in the press).
9. Mouschovias, T. Ch., Shu, F. H. & Woodward, P. R. *Astr. Astrophys.* **33,** 73–77 (1974).
10. Blitz, L. & Shu, F. H. *Astrophys. J.* **238,** 148–157 (1980).
11. Asseo, E., Cesarsky, C. J., Lacheze-Rey, M. & Pellat, R. *Astrophys. J.* **225,** L21–L25 (1978).
12. Parker, E. N. *Cosmical Magnetic Fields,* 532–611 (Clarendon, Oxford, 1979).
13. Matsumoto, R., Horiuchi, T., Shibata, K. & Hanawa, T. *Publs. Astr. Soc. Japan* **40,** 171–195 (1988).
14. Matsumoto, R., Horiuchi, T., Hanawa, T. & Shibata, K. *Astrophys. J.* **356,** 259–271 (1990).
15. Shibata, K. *et al. Astrophys. J.* **338,** 471–492 (1989).
16. Fujimoto, M. in *IAU Symp.* No. 29 (ed. Arakeljan, M.) 453–463 (Izdatel'stvo Akademii Nauk Armyanski SSR, 1968).
17. Maddalena, R. J., Morris, M., Moscowitz, J. & Thaddeus, P. *Astrophys. J.* **303,** 375–391 (1986).
18. Appenzellar, I. *Astr. Astrophys.* **36,** 99–105 (1974).
19. Shibata, K. & Uchida, Y. *Publs. Astr. Soc. Japan* **37,** 31–46 (1985).
20. Bally, J., Langer, W. D., Stark, A. A. & Wilson, R. W. *Astrophys. J.* **312,** L45–L49 (1987).
21. Goldsmith, P. F. & Arquilla, R. in *Protostars and Planets II* (eds Black, D. C. & Matthews, M. S.) 137–149 (University of Arizona Press, Tucson, 1985).
22. Beck, R., Loiseau, N., Hummel, E., Berkhuijsen, E. M. & Wielebinski, R. *Astr. Astrophys.* **222,** 58–68 (1989).
23. Bajaja, E., Berkhuijsen, E. M. & Beck, R. in *IAU Symp.* No. 140 (eds Beck, R. *et al.*) 203–204 (Kluwer, Dordrecht, 1990).

ACKNOWLEDGEMENTS. We thank the referee, B. Elmegreen, for helpful comments, A. McAllister for his help in revising the manuscript, and R. Beck, M. Chiba, M. Fujimoto, Y. Fukui, T. Hanawa, T. Hasegawa, N. Nakai, S. Miyama, T. Nakano, T. Sawa, Y. Sofue, K. Tatematsu and Y. Uchida for discussions.