ABSTRACT

We investigate numerically the combined effects of supersonic turbulence, strong magnetic fields, and ambipolar diffusion on cloud evolution leading to star formation. We find that in clouds that are initially magnetically subcritical, supersonic turbulence can speed up star formation, through enhanced ambipolar diffusion in shocks. The speedup overcomes a major objection to the standard scenario of low-mass star formation involving ambipolar diffusion, since the diffusion timescale at the average density of a molecular cloud is typically longer than the cloud lifetime. At the same time, the strong magnetic field can prevent the large-scale supersonic turbulence from converting most of the cloud mass into stars in one (short) turbulence crossing time and thus alleviate the high efficiency problem associated with the turbulence-controlled picture for low-mass star formation. We propose that relatively rapid but inefficient star formation results from supersonic collisions of somewhat subcritical gas in strongly magnetized turbulent clouds. The salient features of this shock-accelerated, ambipolar diffusion-regulated scenario are demonstrated with numerical experiments.

Subject headings: ISM: clouds — ISM: magnetic fields — MHD — stars: formation — turbulence

1. INTRODUCTION

The standard scenario of low-mass star formation envisions quasi-static condensation of dense cores out of magnetically subcritical clouds and inside-out core collapse leading to star formation (Shu et al. 1987; Mouschovias & Ciolek 1999). An alternative is the turbulence-controlled star formation, with magnetic fields playing a minor role if any (Larson 1981; Mac Low & Klessen 2004). In this picture, dense cores arise from compression in the supersonic turbulence observed in molecular clouds (Padoan et al. 2001; Gammie et al. 2003; Li et al. 2004). The cores so formed are transient entities, however. Even though some of them may have column density distributions resembling those of static Bonnor-Ebert spheres, their internal motions are typically dynamic, with transonic or even supersonic speeds (Ballesteros-Paredes et al. 2003), which are difficult to reconcile with the subsonic internal motions inferred in low-mass starless cores (Lee et al. 1999; Tafalla et al. 2004). A potentially more serious difficulty with this picture is the rate and efficiency of star formation. Numerical simulations have shown that supersonic turbulence decays in one free-fall time or less, with or without a strong magnetization (Mac Low et al. 1998; Stone et al. 1998; Padoan & Nordlund 1999). Without additional support, self-gravitating clouds would collapse in one free-fall time, leading to a rate of star formation well above that inferred on the Galactic scale (Evans 1999). Also, stars in typical low-mass star-forming clouds contain less than a few percent of the cloud mass. Such a low star formation efficiency is not naturally explained.

Excessive star formation is avoided in the standard scenario by an ordered magnetic field, which is postulated to provide most of the cloud support. The gradual weakening of magnetic support through ambipolar diffusion leads to core formation. The cores so formed tend to have subsonic infall speeds consistent with observations (Li 1999; Ciolek & Basu 2000). However, calculations based on this scenario have so far avoided a direct treatment of turbulence by starting from relatively quiescent regions of moderately high density (several times $10^3$ cm$^{-3}$ or higher), as opposed to the average cloud density (a few times $10^2$ cm$^{-3}$ or lower; Blitz 1993). How the overdense regions form out of the more turbulent background in the first place was not addressed. It is unlikely for them to have condensed out quasi-statically through ambipolar diffusion, because the level of ionization in the background is enhanced over the value given by cosmic-ray ionization alone (McKee 1989), as a result of photionization of interstellar far-ultraviolet radiation field. The enhancement makes the timescale for quiescent ambipolar diffusion at the average density longer than the cloud lifetime (Myers & Khersonsky 1995). In this Letter, we show that the supersonic turbulence observed in molecular clouds can speed up ambipolar diffusion in localized regions through shock compression without turning most of the cloud mass into stars in one crossing time.

2. PROBLEM FORMULATION

We consider strongly magnetized sheetlike clouds, taking advantage of the tendency for cloud material to settle along field lines into a flattened configuration. The basic formulation that we adopt here is the same as that of Nakamura & Li (2002, 2003) and Li & Nakamura (2002), which was originally developed for treating ambipolar diffusion-driven fragmentation of quiescent magnetic clouds in the presence of small perturbations (see also Indebetouw & Zweibel 2000 and Basu & Ciolek 2004). Briefly, we assume that the fluid motions are confined to the plane of the sheet, with force balance maintained in the vertical direction at all times (Fiedler & Mouschovias 1993). The cloud evolution is governed by a set of vertically integrated MHD equations that include ambipolar diffusion. We consider the case where the magnetic field is coupled to the bulk neutral cloud material through ion-neutral collision, with ion density proportional to the square root of neutral density. A canonical value of $3 \times 10^{-16}$ cm$^{-3}$ g$^{-1/2}$ is adopted for the proportionality constant (Elmegreen 1979). We solve the hydrodynamic part of the governing equations using Roe’s total variation diminishing method and determine the gravitational and magnetic potentials outside the sheet using a convolution method based on fast Fourier transform. The computation timestep is chosen small enough to satisfy both the CFL con-
We consider an initially uniform mass distribution in the $x$-$y$ plane, with column density $\Sigma_0 = 4.68 \times 10^{-3} A_v$ g cm$^{-2}$ (where $A_v$ is visual extinction for standard grain properties). The cloud is assumed isothermal, with sound speed $c_s = 1.88 \times 10^3 T_0^{1/2}$ cm s$^{-1}$ (where $T_0$ is the temperature in units of 10 K). Above a critical column density $\Sigma_c = 10^2 \Sigma_0$, the equation of state is stiffened to enable simulation beyond the Jeans length. We adopt the thin-sheet approximation.

To mimic the turbulent motions observed in molecular clouds, we stir the cloud with a supersonic velocity field at $t = 0$ by the same random velocity field of Mach number $M = 10$. The color bar is for column density (in units of the initial value $\Sigma_0$). The time labeled is in units of the gravitational collapse time, and the length unit is the Jeans length. Shown in each panel are contours of critical flux-to-mass ratio (in white) and the velocity field (in arrows). The arrow length is proportional to the flow speed, with normalization indicated above the panel.

Two representative clouds are considered in detail, one magnetically subcritical with $\Gamma_c = 1.2$ and the other supercritical with $\Gamma_c = 0.8$. We choose a Mach number $M = 10$, which yields a turbulence crossing time $t_x \equiv 10 L_\perp/(2 M c_s) = 0.5 t_c$. The results are displayed in Figures 1 and 2.
of powerful protostellar outflows (Matzner & McKee 2000; Shu et al. 2004).

We begin with the subcritical cloud. Its snapshots are displayed in the first five panels of Figure 1. Figure 1a shows the cloud after about one turbulence crossing time (at $t = 0.448$, in units of $t_0$ here and below), when a large fraction of the cloud mass has been compressed into a network of filaments. The filaments would collapse quickly were it not for the strong magnetic fields trapped in them. By $t = 0.955$ (Fig. 1b), they are well on their way to reexpansion, leaving behind little dense supercritical material (which has a mass fraction of the order of 5% according to Fig. 2). Although most of the shocked regions do not collapse right away, they are permanently altered. Their flux-to-mass ratios are changed by ambipolar diffusion, whose rate is enhanced by the increase in both density (which weakens the field-matter coupling) and gradient of the field strength. The magnetically altered regions cannot return to their precompression uniformly magnetized state after shock passage. Rather, a magnetically differentiated structure develops, with regions of relatively low flux-to-mass ratio embedded within a more strongly magnetized background. The supercritical "islands" are marked by white contours in each panel. These regions have a head start over their subcritical surroundings in forming stars, through further turbulent compression and/or ambipolar diffusion. (We have tested our standard simulation of $\Gamma_0 = 1.2$ in the limit of zero ambipolar diffusion and found that the $B/\Sigma$ ratio remains constant to within $10^{-4}$.)

After the initial phase of strong compression and reexpansion, the cloud settles down to a more relaxed configuration. An example of this new phase of cloud evolution is shown in Figure 1c. Prominent at this time ($t = 1.59$ or 3.0 Myr; adopting here and below the fiducial combination $T_{\text{in}} = 1$ and $A_p = 1$, appropriate for Taurus clouds according to Arce & Goodman 1999) are several supercritical filaments, the densest parts of which have already begun dynamic contraction and formed collapsed objects. Note that the dense star-forming regions are well separated, reminiscent of the dispersed mode of star formation observed in Taurus-like clouds. Once created by large-scale compression at well-separated locations, the dense regions stay apart because their mutual gravitational attraction is canceled to a large extent by the magnetic repulsion between them. This mode is illustrated further in Figure 1d, where $t = 2.88$ (or 5.5 Myr) and $\sim 10\%$ of the cloud mass now resides in the dense supercritical regions. Note that the dense "ridge" at the bottom left corner has a much lower velocity than its surrounding medium. This is also true for other high-density regions in general, broadly consistent with the observation that low-mass star-forming cores are more quiescent than their surroundings.

The mass fraction of dense supercritical regions increases steadily, as a result of continued ambipolar diffusion. The steady increase is punctuated by bumps at late times (see Fig. 2). These bumps are produced by interactions of dense regions, which are evident in Figure 1e, where $t = 9.55$ (or 18 Myr). The interactions become more important as more cloud material becomes supercritical, since the gravitational attraction between supercritical regions is not completely offset by magnetic repulsion. The unbalanced "effective" gravity tends to drive the supercritical regions together, which enhances the possibility for further interactions. The clustering of "heavier" supercritical regions against a more strongly magnetized background may, given enough time, drive the cloud from the initial dispersed mode of star formation to a clustered mode of star formation. In the regions where the dense supercritical material preferentially gathers, the local efficiency of star formation can be much higher than the average.

The magnetically supercritical cloud evolves differently. Its snapshots are displayed in the last three panels of Figure 1. Figure 1f shows the cloud at $t = 0.487$, when a network of filaments has formed, as in the subcritical case, although the filaments here are thinner because of a weaker magnetic resistance to shock compression. These filaments are sufficiently supercritical that when enough mass is accumulated, they break up gravitationally into a string of dense cores along their length, unlike their more magnetized counterparts. By the time shown in Figure 1g ($t = 0.955$), some of the dense cores have already merged together, creating several dense supercritical regions. These regions contain about half of the cloud mass (see Fig. 2). They dominate the subsequent cloud evolution through mutual gravitational interactions. By the time shown in Figure 1h ($t = 3.50$), some of the dense regions have merged together, and new blobs have formed through interactions. Most of the dense regions are clustered together gravitationally. The clustering is retarded only moderately by magnetic repulsion, since the cloud is magnetically supercritical as a whole, and the dense regions are even more so. Nearly 20% of the cloud mass does become subcritical, however, as a result of magnetic flux diffusing from the high-density to low-density regions. It may explain why the mass fraction of the dense supercritical regions hovers around half, rather than a value closer to unity as one might naively expect for supercritical clouds.

We have explored the effects of the same (strong) turbulence on clouds with other degrees of magnetization, including one that is critically magnetized everywhere initially ($\Gamma_0 = 1$). Dense supercritical regions are created promptly in this cloud, with a mass fraction intermediate between that of the subcritical ($\Gamma_0 = 1.2$) and supercritical ($\Gamma_0 = 0.8$) cloud, as shown in Figure 2. Also shown in Figure 2 is a more subcritical cloud with $\Gamma_0 = 1.5$. It does not produce a dense supercritical object until $t \sim 5$ (or $\sim 10$ Myr). Such a long dormant time would argue against star-forming clouds being subcritical by a large factor everywhere, although a stronger turbulence can in principle induce localized cloud collapse and star formation sooner. In practice, a distribution of the flux-to-mass ratio $\Gamma_0$ is expected
in realistic clouds. The least magnetized regions are expected to collapse first, either on their own (if they are supercritical and self-gravitating) or through turbulent compression. In such a case, the star formation rate and efficiency would obviously depend on the $\Gamma_0$ distribution, which is unknown at present.

4. DISCUSSION AND CONCLUSIONS

We have demonstrated that star formation with a relatively low efficiency can occur over an extended period of time in highly turbulent, somewhat magnetically subcritical clouds. The low efficiency is made possible by the strong magnetic field, which prevents the global cloud collapse in one turbulence crossing time. The supersonic turbulence, on the other hand, speeds up ambipolar diffusion in localized regions through shock compression. The acceleration of ambipolar diffusion by turbulence has been examined analytically by Kim & Diamond (2002), Zweibel (2002), and Fatuzzo & Adams (2002) and numerically by Heitsch et al. (2004). Our investigation differs from these studies in adopting a highly compressive turbulent flow and in that the cloud dynamics are computed rather than prescribed.

To further illustrate the role of turbulence in star formation, we have rerun the subcritical ($\Gamma_0 = 1.2$) case, varying the turbulent Mach number $\mathcal{M}$ from 0.3 to 10. The result is plotted in Figure 3. For $\mathcal{M} \leq 1$, it takes an order of magnitude longer than the gravitational collapse time to produce the first dense magnetically supercritical object. As $\mathcal{M}$ increases, dense supercritical regions appear earlier. Beyond some critical value ($\mathcal{M} \approx 5$ for our particular examples), such regions form promptly, within one collapse time. The ability for a subcritical cloud to form stars quickly in the presence of a supersonic turbulence removes a major objection to the standard scenario for low-mass star formation through ambipolar diffusion based on cloud lifetime arguments (Hartmann et al. 2001).

Our calculations support the idea of bimodal star formation (Shu et al. 1987). In magnetically subcritical clouds, dense supercritical regions are created by large-scale turbulence at well-separated locations. They stay separated until a large enough fraction of the cloud mass becomes supercritical for the gravitational attraction to overwhelm the magnetic repul-

![Fig. 3.—Time evolution of the mass fraction of the dense regions that have become magnetically supercritical through ambipolar diffusion in a subcritical cloud ($\Gamma_0 = 1.2$), showing the effects of the level of turbulence $\mathcal{M}$.](image)

sion. We identify this mode of star formation with the mode of relatively inefficient, dispersed star formation exemplified by the Taurus clouds. If the cloud lives long enough, a large fraction of the cloud mass will become supercritical sooner or later, through continued ambipolar diffusion. In regions where the supercritical materials collect gravitationally, the star formation efficiency could be much higher than the general background. Such regions could be the sites of efficient cluster formation. Efficient star formation occurs much more quickly if the cloud is initially magnetically supercritical, as in our second example. Our simulations suggest that a realistic turbulence with power dominated by large-scale motions does not fundamentally change the bimodal nature of star formation in magnetic clouds. Three-dimensional calculations are needed to firm up this conclusion.

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REFERENCES

Arce, H. G., & Goodman, A. A. 1999, ApJ, 517, 264
Ballesteros-Paredes, J., Klessen, R. S., & Vazquez-Semadeni, E. 2003, ApJ, 592, 188
Basu, S., & Ciolek, G. E. 2004, ApJ, 607, L39
Blitz, L. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: Univ. Arizona Press), 125
Ciolek, G. E., & Basu, S. 2000, ApJ, 529, 925
Elmegreen, B. G. 1979, ApJ, 232, 729
Evans, N. J., II. 1999, ARA&A, 37, 311
Fatuzzo, M., & Adams, F. C. 2002, ApJ, 570, 210
Fiedler, R. A., & Mouschovias, T. Ch. 1993, ApJ, 415, 680
Gammie, C. F., Lin, Y.-T., Stone, J. M., & Ostriker, E. C. 2003, ApJ, 592, 203
Hartmann, L., Ballesteros-Paredes, J., & Bergin, E. 2001, ApJ, 562, 852
Heitsch, F., Zweibel, E. G., Slyz, A. D., & Devriendt, J. E. 2004, ApJ, 603, 165
Indebetouw, R., & Zweibel, E. G. 2000, ApJ, 532, 361
Kim, E.-J., & Diamond, P. H. 2002, ApJ, 578, L113
Larson, R. B. 1981, MNRAS, 194, 809
Lee, C. W., Myers, P. C., & Tatfulla, M. 1999, ApJ, 526, 788
Li, P. S., Norman, M. L., Mac Low, M.-M., & Heitsch, F. 2004, ApJ, 605, 800
Li, Z.-Y. 1999, ApJ, 526, 806
Li, Z.-Y., & Nakamura, F. 2002, ApJ, 578, 256
Mac Low, M.-M., & Klessen, R. S. 2004, Rev. Mod. Phys., 76, 125
Mac Low, M.-M., Klessen, R. S., Burkert, A., & Smith, M. D. 1998, Phys. Rev. Lett., 80, 2754
Matzner, C. D., & McKee, C. F. 2000, ApJ, 545, 364
McKee, C. F. 1989, ApJ, 345, 782
Mouschovias, T., & Ciolek, G. 1999, in The Origins of Stars and Planetary Systems, ed. C. Lada & N. Kylafis (Dordrecht: Kluwer), 305
Myers, P. C., & Khrersonsvy, V. K. 1995, ApJ, 442, 186
Nakamura, F., & Li, Z.-Y. 2002, ApJ, 566, L101
———. 2003, ApJ, 594, 363
Padoan, P., Juvela, M., Goodman, A. A., & Nordlund, Å. 2001, ApJ, 553, 227
Padoan, P., & Nordlund, Å. 1999, ApJ, 526, 279
Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23
Shu, F. H., Li, Z.-Y., & Allen, A. 2004, ApJ, 601, 930
Stone, J. M., Ostriker, E. C., & Gammie, C. F. 1998, ApJ, 508, L99
Tafalla, M., Myers, P. C., Caselli, P., & Walmsley, C. M. 2004, A&A, 416, 191
Zweibel, E. G. 2002, ApJ, 567, 962