LOWER THE CHARACTERISTIC MASS OF CLUSTER STARS BY MAGNETIC FIELDS AND OUTFLOW FEEDBACK

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ABSTRACT

Magnetic fields are generally expected to increase the characteristic mass of stars formed in stellar clusters, because they tend to increase the effective Jeans mass. We test this expectation using adaptive mesh refinement magnetohydrodynamical simulations of cluster formation in turbulent magnetized clumps of molecular clouds, treating stars as accreting sink particles. We find that, contrary to the common expectation, a magnetic field of the strength in the observed range decreases, rather than increases, the characteristic stellar mass. It (1) reduces the number of intermediate-mass stars that are formed through direct turbulent compression, because sub-regions of the clump with masses comparable to those of stars are typically magnetically subcritical and cannot be compressed directly into collapse, and (2) increases the number of low-mass stars that are produced from the fragmentation of dense filaments. The filaments result from mass accumulation along the field lines. In order to become magnetically supercritical and fragment, the filament must accumulate a large enough column density (proportional to the field strength), which yields a high volume density (and thus a small thermal Jeans mass) that is conducive to forming low-mass stars. We find, in addition, that the characteristic stellar mass is reduced further by outflow feedback. The conclusion is that both magnetic fields and outflow feedback are important in shaping the stellar initial mass function.

Key words: ISM: clouds – ISM: magnetic fields – magnetohydrodynamics (MHD)

1. INTRODUCTION

How the initial mass function (IMF) of stars originates is one of the most basic questions that a complete theory of star formation must answer. It is also one of the most difficult (see reviews by Bonnell et al. 2007; McKee & Ostriker 2007, and references therein). Many ideas have been advanced to explain the IMF, e.g., Zinnecker (1982), Adams & Fatuzzo (1996), Elmegreen (1997), Padoan & Nordlund (2002), Larson (2003), Shu et al. (2004), Hennebelle & Chabrier (2008), and Kunz & Mouschovias (2009), among others. Particularly intriguing is the proposal by Padoan & Nordlund (2002) that the IMF is essentially determined by the supersonic turbulence, which controls the density distribution in the highly inhomogeneous clouds. They used the Jeans criterion to determine analytically the mass distribution of the gravitationally unstable regions, which was taken to represent the stellar IMF. Both ingredients of the theory, the turbulent structuring of cloud density and the criterion for gravitational collapse, are strongly affected, however, by a dynamically important magnetic field. Some magnetic effects on the IMF, such as the magnetic cushion of turbulent compression (Padoan & Nordlund 2002) and the additional cloud support by magnetic pressure (Hennebelle & Chabrier 2008), can be incorporated into the analytic theory approximately. Other equally, if not more, important magnetic effects are not captured by the theory and will be the focus of our investigation.

Our study will concentrate on the parsec-scale, cluster-forming dense clumps of molecular clouds, where the majority of stars, especially massive stars, are thought to originate (Lada & Lada 2003), and where magnetic fields have been observed in some cases. For example, in the nearest region of active massive star formation, OMC-1, a well-ordered field is inferred from polarized dust emission (e.g., Vaillancourt et al. 2008). Crutcher et al. (1999) obtained, from CN Zeeman measurements, a line-of-sight field strength $B_{los} = 360 \mu G$ for this region, which corresponds to a dimensionless mass-to-flux ratio $\lambda = 2\pi G^{1/2} M / \Phi \sim 4.5$. The ratio is close to the median value $\lambda \sim 6$ obtained by Falgarone et al. (2008) for a sample of dense clumps of massive star formation. Correcting for the projection effects may reduce the ratio by a factor of 2–3 (Shu et al. 1999), yielding a median value for the intrinsic mass-to-flux ratio of 2–3.

A magnetic field corresponding to a $\lambda$ of a few would not be strong enough to support the clump against gravitational collapse by itself. It can, however, change the mass distribution of the stars formed. This is because individual stars form out of sub-regions of the clump, which are generally more strongly magnetized (relative to their masses) than the clump as a whole (i.e., with smaller values of $\lambda$; Tilley & Pudritz 2007; Dib et al. 2007), because the mass of a region (which is proportional to volume) decreases faster with its size than the magnetic flux (which is proportional to area). In particular, sub-regions smaller than the clump by a factor comparable to $\lambda$ are expected to be magnetically subcritical (with $\lambda < 1$) in general. It would be hard to directly compress such regions into collapse by turbulence in the ideal magnetohydrodynamic (MHD) limit (see, however, Nakamura & Li 2005 and Basu et al. 2009 for studies that include ambipolar diffusion). Another effect is that the magnetic forces act on the turbulent flows anisotropically, channeling matter along the field lines into dense, flattened structures that can subsequently fragment thermally.

In this Letter, we seek to quantify the above effects using the cluster formation simulations of Wang et al. (2010), which were
carried out with an adaptive mesh refinement (AMR) MHD code that includes sink particles and outflow feedback. We find, in Section 2, that the characteristic mass of the IMF is lowered by both the magnetic field and outflow feedback. The lowering of the characteristic stellar mass by magnetic fields is somewhat counterintuitive. It is interpreted physically using a so-called magnetically critical Jeans mass (Equation (6)) in Section 3.

2. RESULT

In Wang et al. (2010), we simulated cluster formation in moderately condensed, isothermal \((T = 20 \text{ K})\), clump of 2 pc in size and \(1641 \, M_\odot\) in mass. We added to the clump, one by one, an initial turbulent velocity field of rms Mach number 9 (Model HD), an initially uniform magnetic field of \(100 \, \mu G\) (corresponding to a dimensionless mass-to-flux ratio of 1.4 for the clump as a whole and a larger value of 3.3 for the central, high-density part; Model MHD), and mechanical feedback from collimated outflows driven by accreting stellar objects (Model WIND). For simulation details, we refer the reader to Wang et al. (2010), where we also presented results on the global star formation rate and especially the formation of the most massive object in each simulation. Here, we will concentrate on the distribution of the stellar masses, with an emphasis on low- and intermediate-mass objects.

Figure 1 shows the stellar mass distributions for all three models. It is a log-linear plot of the number of stars in logarithmic mass bins of \(\Delta [\log(M)] = 0.2\) for Models HD (dashed), MHD (solid), and WIND (dotted), when 16% of the clump mass has been converted into stars.

Before proceeding to analyze the numerically obtained mass distributions in Figure 1, we should caution the reader that the mass of a star can be affected by many factors that are only crudely modeled in the current generation of large-scale cluster formation simulations, including our own. These include (1) outflow feedback, which can potentially remove a large fraction and perhaps the majority of the mass of a star-forming core (Shu et al. 1987; Matzner & McKee 2000; Myers 2008), (2) magnetic fields, which affect not only how dense cores form but also how they collapse, and (3) radiative feedback which, once a protostellar system (protostar plus disk) appears, heats up the circumstellar material and suppresses fragmentation close to the central object (e.g., Krumholz et al. 2007; Offner et al. 2009; Price & Bate 2009; Smith et al. 2009; Urban et al. 2010). It is currently not feasible to simultaneously treat all these factors in detail. Our strategy is to focus on magnetic fields and outflow feedback, which are less well studied, and to treat the effects of radiative feedback as simply as possible.

Specifically, we crudely capture the suppression of fragmentation near a star due to radiative feedback using a sink-particle merging algorithm, following Krumholz et al. (2004; see also discussion in Federrath et al. 2010). It eliminates very low mass \(< M_{\text{merg}} = 0.01 \, M_\odot\) sink particles within a distance \(l_{\text{merg}} = 1000 \, \text{AU}\) of an existing star (with mass \(> M_{\text{merg}}\)). Experimentation shows that increasing \(M_{\text{merg}}\) to 0.1 \(M_\odot\) does not significantly change the star formation rate or the stellar mass distribution. The adopted merging distance \(l_{\text{merg}}\) is comparable to the radius of the so-called sphere of thermal influence (where the temperature of the radiatively heated protostellar envelope drops to the ambient value) of an object of solar mass and luminosity (see Equation (14) and Figure 2 of Adams & Shu 1985).
Figure 3. Locations of the so-called HD excess stars (circled) at a representative time $t = 0.498$ Myr on a column density map. The box size is $L = 2$ pc.

Table 1

| Model | IMF Exponent $\Gamma$ | Characteristic Mass $M_{ch}$ | $\Delta^a$ | Star Number |
|-------|-----------------------|-------------------------------|------------|-------------|
| HD    | $-1.2$                | $5.0 M_\odot$                | $0.8$      | $96$        |
| MHD   | $-1.4$                | $1.3 M_\odot$                | $0.8$      | $119$       |
| WIND  | $-1.0$                | $0.5 M_\odot$                | $1.8$      | $203$       |

Note. $^a$ Full width of $\log(M)$ at half-maximum of the stellar mass distribution.

We find that increasing $l_{merg}$ from 1000 AU to 2000 AU has little effect on the star formation rate and stellar mass distribution.Decreasing it to 600 AU (or three times the size of the finest cell) does not change the total star formation rate, but can change the number and masses of stars significantly, by up to 50%. We believe, however, that the smaller merging distance is less realistic, since the gas on the smaller scale is expected to be more strongly heated. The larger merging distance prevents a collapsing core from breaking up into many small pieces, in agreement with the fact that the best observed cores in nearby star-forming regions typically harbor one, at most a few, stellar system (e.g., Mundy et al. 2000). Nevertheless, in view of our crude representation of radiative feedback, we elect to focus on the difference between the stellar mass distributions of the three simulations, which use the same sink-particle treatment, rather than the distributions themselves.

The magnetic field is solely responsible for the difference between Models HD and MHD. From Figure 1, we see that its main effects are to reduce the number of intermediate-mass stars with masses around $\sim 4 M_\odot$, and to increase the number of lower mass stars with masses around $\sim 1 M_\odot$. To be more quantitative, we fit the high mass end of the distribution with a power law, $dN/d \log(M) \propto M^\Gamma$, as shown in Figure 2. In all three cases the mass distribution deviates sharply from the power-law fit below a characteristic mass, $M_{ch}$ (sometimes dubbed the “knee” of the IMF; e.g., Bonnell et al. 2006). The values of $M_{ch}$ and power-law index $\Gamma$ are listed in Table 1. Note that the characteristic mass of $\sim 5 M_\odot$ in Model HD is not far from the initial Jeans mass near the clump center, $\sim 9.5 M_\odot$, consistent with Bonnell et al. (2006). The power indexes are not well determined because of the limited number of stars in the power-law regime. Nevertheless, they are all comparable to the Salpeter value within uncertainties. The characteristic masses are, however, significantly different. In particular, the magnetic field in Model MHD has apparently lowered the characteristic mass by a factor of $\sim 4$ compared to that in Model HD.

To help understand why the field hampers the formation of intermediate-mass stars, we show in Figure 3 a snapshot of the so-called HD excess stars, defined somewhat arbitrarily as those stars in HD model in Figures 1 and 2 with masses in the three mass bins between $10^{1.2}$ and $10^{1.8} M_\odot$. The majority of these stars are produced at relatively isolated regions, by localized converging flows in the initial turbulence. Such regions are largely absent in the MHD model, where a moderately strong global magnetic field is present. The reduction in the number of intermediate-mass stars makes the stellar mass distribution significantly narrower in the MHD model than in the HD model (see Table 1 and Figures 1 and 2).

The magnetic field in the MHD model interacts strongly with the turbulence. It changes the “texture” of the turbulent clump, by not only resisting the cross-field turbulent compression, but also promoting mass accumulation along the field lines into flattened sheets or filaments. Figure 4 shows an example of the (flattened) filaments resulted from the intrinsically anisotropic magnetic forces. It is in such magnetically induced filaments that the majority of the stars in the MHD model form. As we discuss in Section 3, the high density in the filaments favors the formation of low-mass stars, which are more numerous compared with the non-magnetic HD model.

Outflow feedback is responsible for the difference between Models WIND and MHD. From Figures 1 and 2, it is clear
that the outflows have (1) shifted the characteristic mass $M_{\text{sh}}$ to a lower value, from $\sim 1.3 M_\odot$ to $\sim 0.5 M_\odot$, and (2) nearly doubled the number of stars, from 119 to 203 (see Table 1). The lowering of the stellar mass by outflow feedback is perhaps not too surprising, because, individually, the outflow from a given star can remove part of the dense envelope that feeds the growing star (Shu et al. 1987; Matzner & McKee 2000; Myers 2008) and, collectively, the feedback from all stars can prevent the clump from rapid global collapse (Nakamura & Li 2007; Wang et al. 2010), lowering the total rate of stellar mass accretion. There is, however, a large spread in both the rate and the duration of the mass accretion in stars of similar masses. The spread makes it difficult to precisely develop a complete picture of how the outflows lower the characteristic stellar mass. The number of stars produced per unit time (i.e., the stellar production rate) turns out to be insensitive to the outflow feedback. It takes longer, however, to convert the same amount of gas into stars in the presence of the feedback, which is the main reason for the larger number of stars in Model WIND than in Model MHD.

3. DISCUSSION AND CONCLUSION

We have shown that a magnetic field of strength in the observed range changes the IMF significantly, by impeding direct turbulent compression of relatively low density material into relatively massive stars and, more importantly, promoting the formation of dense, flattened structures that subsequently fragment preferentially into low-mass stars.

The basic reason for the magnetic field to impede direct turbulent fragmentation is that a sub-region of the clump that is magnetically subcritical cannot be compressed into prompt collapse by turbulence. For a region of size $l$ in a clump of average field strength $B_0$ and mass density $\rho_0$, the characteristic dimensionless mass-to-flux ratio is

$$\lambda = \frac{2\pi G^{1/2} M_l}{\Phi_l} \sim \frac{2\pi G^{1/2} \rho_0 l^3}{B_0 l^2} = \frac{2\pi G^{1/2} \rho_0 l}{B_0},$$  \hspace{1cm} (1)

which indicates that regions smaller than the characteristic size,

$$l_B = \frac{B_0}{2\pi G^{1/2} \rho_0},$$  \hspace{1cm} (2)

are typically magnetically subcritical (with $\lambda < 1$). The characteristic size is related to the clump size $L$ by $l_B \sim L/\lambda_{cp}$ (where “$\text{cp}$” stands for “clump”), since the mass-to-flux ratio of the clump as a whole is $\lambda_{cp} \sim 2\pi G^{1/2} \rho_0 L/B_0$, according to Equation (1). In other words, a typical region that is smaller than the clump by a factor of $\sim \lambda_{cp}$ cannot be directly compressed into collapse by turbulence. The corresponding characteristic mass is

$$M_B \sim \rho_0 l_B^3 \sim \frac{\rho_0 L^3}{\lambda_{cp}^3} \sim \frac{M_{\text{cp}}}{\lambda_{cp}^3} \sim 64 \left( \frac{M_{\text{cp}}}{10^4 M_\odot} \right) \left( \frac{2.5}{\lambda_{cp}} \right)^3 (M_\odot),$$  \hspace{1cm} (3)

where we have scaled the clump mass $M_{\text{cp}}$ by $10^3 M_\odot$ and the clump mass-to-flux ratio by 2.5, comparable to the (projection corrected) median value inferred from CN Zeeman observations (see discussion in Section 1).

The characteristic mass $M_B$ is essentially the magnetic Jeans mass at the average clump density (see Equation (41) of McKee 1999, which gives a numerical value three times larger). It is to be compared with the average thermal Jeans mass

$$M_l \approx \frac{4.1}{1 \text{ pc}} \left( \frac{l}{1 \text{ pc}} \right)^{3/2} \left( \frac{10^3 M_\odot}{M_{\text{cp}}} \right)^{1/2} \left( \frac{T}{10^4 \text{ K}} \right)^{3/2} (M_\odot),$$ \hspace{1cm} (4)

(e.g., Spitzer 1978). The average magnetic Jeans mass $M_B$ is therefore typically larger than the average thermal Jeans mass $M_l$, indicating that the formation of those stars with masses comparable to $M_l$ or smaller by direct turbulent compression can be strongly hindered by the magnetic field. The most massive stars are expected to be least affected by the magnetic field. However, their formation may be governed more by the global clump collapse (retarded by outflow feedback and magnetic fields) than by direct turbulent compression (Wang et al. 2010; see also Smith et al. 2009). Indeed, massive ($> 10 M_\odot$) stars in Model MHD contain more mass than those in Model HD, indicating that their formation is not hampered by magnetic fields, unlike intermediate-mass stars.

The magnetic field can also promote fragmentation, because the magnetic forces are intrinsically anisotropic. It is easier for the turbulent flows to move material along the field lines than across them. The net result is the formation of flattened, sheet- or filament-like condensations, which are conducive to fragmentation. Larson (1985) estimated the Jeans mass for a self-gravitating sheet (thermally supported in the vertical direction) to be

$$M_{1,sh} \approx \frac{4.67 a^4}{G^2 \Sigma},$$ \hspace{1cm} (5)

where $a$ is the isothermal sound speed and $\Sigma$ is the column density. In order to form stars, the sheet must first become magnetically supercritical, with a column density greater than the critical value $\Sigma_{cr} = B_0/(2\pi G^{1/2})$. Substituting $\Sigma_{cr}$ into Equation (5), we have

$$M_{1,cr} \approx 9.34 \frac{a^4}{G^{3/2} B_0} = 0.78 \left( \frac{L}{1 \text{ pc}} \right)^2 \times \left( \frac{10^3 M_\odot}{M_{\text{cp}}} \right) \left( \frac{T}{10 \text{ K}} \right)^2 \left( \frac{\lambda_{cp}}{2.5} \right) (M_\odot),$$ \hspace{1cm} (6)

which is the mass expected for stars formed through thermal fragmentation of magnetically critical filaments. A similar, but somewhat smaller, characteristic mass $M_0 = \pi^2 a^4/(G^3 B_0)$ was defined in Shu et al. (2004) in their study of the collapse of magnetized singular isothermal spheres. The important conceptual point is that the magnetically critical Jeans mass $M_{1,cr}$ (or $M_0$) decreases with an increasing magnetic field strength, because a stronger magnetic field can support a higher column density, which in turn leads to a higher volume density (due to gravitational compression along the field lines) and thus a lower thermal Jeans mass. It should be relatively insensitive to turbulence, which is expected to be weak at the relevant (high) densities. In any case, the magnetically critical Jeans mass is typically smaller than the average thermal Jeans mass, by a factor

$$M_{1,cr} \approx \frac{0.19}{(L/1 \text{ pc})^{1/2}} \left( \frac{10^3 M_\odot}{M_{\text{cp}}} \right)^{1/2} \left( \frac{T}{10 \text{ K}} \right)^{1/2} \left( \frac{\lambda_{cp}}{2.5} \right),$$ \hspace{1cm} (7)

which is relatively insensitive to clump parameters. It is therefore not too surprising that a moderately strong field can significantly lower the characteristic mass of the stars formed in a cluster, as we found numerically. Magnetism is another way of setting a stellar mass scale that is distinct from the one advocated by Larson (2005), based on detailed thermal physics of molecular cloud material (e.g., Jappsen et al. 2005; Bonnell et al. 2006).
To summarize, we have demonstrated through both AMR MHD simulations (Section 2) and analytic considerations (Equations (1)–(7)) that moderately strong magnetic fields of the observed strengths (corresponding to a dimensionless mass-to-flux ratio of a few) are important in shaping the mass distribution of stars produced in turbulent, cluster-forming, dense clumps. The basic reason is that the field interacts strongly with the turbulent flows, which affects how the flows create regions unstable to gravitational collapse and star formation. The magnetic field prevents sub-regions of the clump that are magnetically subcritical (with masses less than the average magnetic Jeans mass \( M_{J,c} \)) from being compressed directly into collapse by the turbulence. The magnetic resistance to turbulent compression has apparently reduced the number of intermediate-mass stars formed in our simulations. More importantly, the intrinsically anisotropic magnetic forces channel part of the clump material along the field lines into dense structures, where the high density promotes the formation of low-mass stars with masses comparable to the magnetically critical Jeans mass \( M_{J,c,r} \), which lowers the characteristic stellar mass. The mass is further reduced by outflow feedback, which affects not only the individual stars that drive the outflows, but also the dynamics of the clump as a whole. We conclude that magnetic fields and outflow feedback are important factors that should be accounted for in a complete theory of the stellar IMF.

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