Collapse and Fragmentation of Magnetic Molecular Cloud Cores with an AMR Code

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Formation and Early Evolution of Very Low Mass Stars and Brown Dwarfs
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Companions of solar-type stars

Two different mechanisms for binary and planet formation

Udry 2010

Brown-dwarf desert

Exoplanets

log(m₂ sin i) [M_☉]

Binaries

Halbwachs et al. 2003
brown-dwarf desert vs. planets? (25 M_{\text{Jup}}?)

Sahlmann et al. 2011: RV & Hipparcos

<- known to have stellar masses

<- remaining brown dwarf candidates
Midplane density (L) and temperature (R) contours at the center of an initially oblate, magnetic cloud core that has collapsed, rebounded, and fragmented into a quadruple protostar system with fragment masses less than a Jupiter mass (sub-Jeans mass) after $2.615 \, t_{ff}$. Boxed region shown is 6.4 AU wide.
Adaptive Mesh Refinement (AMR) Codes

- AMR codes allow grid points to be inserted where they are needed and removed where they are not needed, for the efficient calculation of problems with varying length scales, e.g., molecular cloud collapse and fragmentation into multiple protostar systems.
- Several AMR codes exist and are available for downloading (e.g., FLASH, enzo, RAMSES, FISH, CHARM, …).
- Enzo (meaning “circle” in Japanese) is used here (Collins et al. 2010).
- Enzo performs ideal magnetohydrodynamics (MHD) using the piecewise parabolic method (PPM) of hydrodynamics and the constrained transport MHD method to preserve the zero divergence of the magnetic field (Collins et al. 2010).
- Enzo has been extensively tested on a wide variety of MHD problems.
- Enzo includes flux-limited diffusion approximation radiative transfer, needed for future comparisons with previous pseudo-MHD models (e.g., Boss 2001).
- Enzo includes as a standard test case the Boss & Bodenheimer (1979) 3D calculation for molecular cloud collapse and fragmentation.
Boss & Bodenheimer (1979) Test Case

- Uniform density and temperature sphere in solid body rotation - artificial initial conditions that are easy to reproduce

- Motivated by Black & Bodenheimer (1976) 2D rotating collapse calculations, which found that rings could form, likely to fragment into multiple protostar systems

- Initial 50% $m = 2$ density perturbation grows and fragments cloud into a binary protostar system

- Isothermal thermodynamics - $T = 10$ K - assumed throughout the collapse

- Often used to test 3D hydro codes (e.g., Burkert & Bodenheimer 1993; Bate et al. 1995; Sigalotti 1997; Kitsionis & Whitworth 2002; Arreaga-Garcia et al. 2007)

- Nonisothermal version of test case calculated with two 3D radiative hydrodynamics codes by Myhill & Boss (1993) - compressional heating and radiative cooling (Eddington or diffusion approximations)

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**Fig. 4a**—Equidensity contours in the equatorial plane, showing the inner portion of the cloud as calculated by $2.70 \times 10^5$ years (1.54 initial free-fall times). **Contour interval:** factor 2.15; **maximum density:** $4.38 \times 10^{-13}$ g cm$^{-3}$. **Fig. 4b**—Equidensity contours in the equatorial plane, showing the inner portion of the cloud as calculated by $2.70 \times 10^5$ years (1.54 initial free-fall times). **Contour interval:** factor 2.15; **maximum density:** $4.38 \times 10^{-13}$ g cm$^{-3}$.
This work: Enzo, B&B isothermal test case, 50% m = 2

\[ t_{ff} > 0.97 \]

\[ 0.70 t_{ff} > \]

\[ < 0 t_{ff} \]

\[ < 0.97 t_{ff} \]

\[ 1.1 t_{ff} > \]
Price & Bate (2007): SPH MHD B&B Test Case (10% m =2)

B perpendicular to rotation axis

B parallel to rotation axis
Burzle et al. (2011): SPH, B parallel to rotation axis, 10% m = 2

\[ B_i = 203 \mu G > \]

\[ < B_i = 407 \mu G \]

\[ B_i = 81.3 \mu G > \]

\[ < B_i = 108 \mu G \]
This work: Enzo, B parallel to rotation axis, 10% m = 2

\[
\begin{align*}
\langle B_i \rangle &= 400 \, \mu G \\
B_i &= 800 \, \mu G \\
\langle B_i \rangle &= 1200 \, \mu G \\
B_i &= 1400 \, \mu G 
\end{align*}
\]
This work: Enzo, $B$ perpendicular to rotation axis, $10\% \, m = 2$

$B_i = 1000 \, \mu G >$

$< B_i = 400 \, \mu G$

$B_i = 1200 \, \mu G >$

$< B_i = 1400 \, \mu G$
This work: Enzo, $B$ parallel to rotation axis, 50% $m = 2$

$\langle B_i \rangle = 600 \, \mu G$

$B_i = 1400 \, \mu G >$

$\langle B_i \rangle = 1600 \, \mu G$

$B_i = 1800 \, \mu G >$
This work: Enzo, $B$ perpendicular to rotation axis, 50% $m = 2$

$< B_i = 300 \, \mu G$

$B_i = 600 \, \mu G$

$< B_i = 800 \, \mu G$

$B_i = 1000 \, \mu G$
Magnetic B&B Test Case Results: 50% m = 2 density perturbations

<table>
<thead>
<tr>
<th>model name</th>
<th>initial Bx</th>
<th>initial By</th>
<th>initial Bz</th>
<th>result time ($t_{ff}$)</th>
<th>result</th>
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B specified in microgauss
### Magnetic B&B Test Case Results: 10% m = 2 density perturbations

B specified in microgauss

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Conclusions for 10% $m = 2$

- Price & Bate (2007) found a critical value of $B_i < 200$ $\mu$G for fragmentation with magnetic field parallel to rotation axis
- Burzle et al. (2011) found a critical value of $B_i < 400$ $\mu$G
- This work finds a critical value of $B_i < 1100$ $\mu$G

- Price & Bate (2007) found a critical value of $B_i < 163$ $\mu$G for fragmentation with magnetic field perpendicular to rotation axis
- This work finds a critical value of $B_i < 1100$ $\mu$G

- Burzle et al. (2011) found a critical value of $B_i < 800$ $\mu$G for collapse with magnetic field parallel to rotation axis
- This work finds a critical value of $B_i < 1400$ $\mu$G

- Collapse and fragmentation for higher B fields in present work is likely due to isothermal EOS rather than polytropic EOS
Conclusions for 50% m = 2

- This work finds a critical value of $B_i < 1600 \, \mu G$ for fragmentation with magnetic field parallel to rotation axis.
- This work finds a critical value of $B_i < 600 \, \mu G$ for fragmentation with magnetic field perpendicular to rotation axis.
- Evidently initial magnetic fields parallel to the rotation axis are less effective at preventing collapse and fragmentation than fields perpendicular to the rotation axis, as expected: flow down the field lines is not impeded by rotational effects when both the magnetic field and the rotational axis are aligned.
- Larger density perturbations favor collapse and fragmentation.
Future Work

- Use Enzo to recalculate models explored with Boss pseudo-MHD code: rotating, centrally-condensed, prolate and oblate, magnetic dense cloud cores, including radiative transfer in the diffusion approximation and ambipolar diffusion of the magnetic field, leading to dynamic cloud collapse and fragmentation.

- Determine the lower mass limit for self-gravitating clumps formed by fragmentation during the collapse of magnetic dense cloud cores, and follow the evolution of these clumps as they evolve by mergers and accretion in their protostellar disks.