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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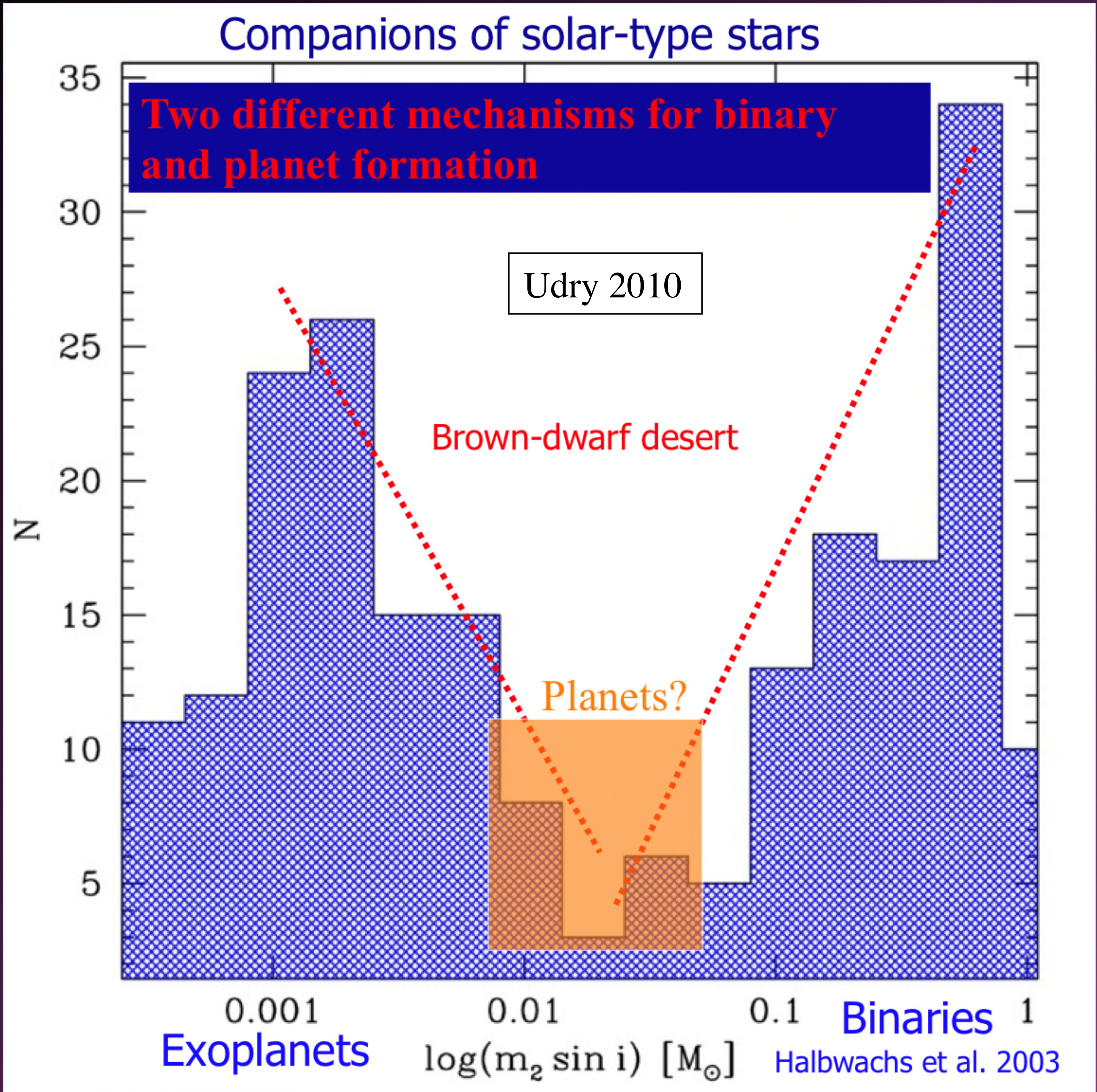
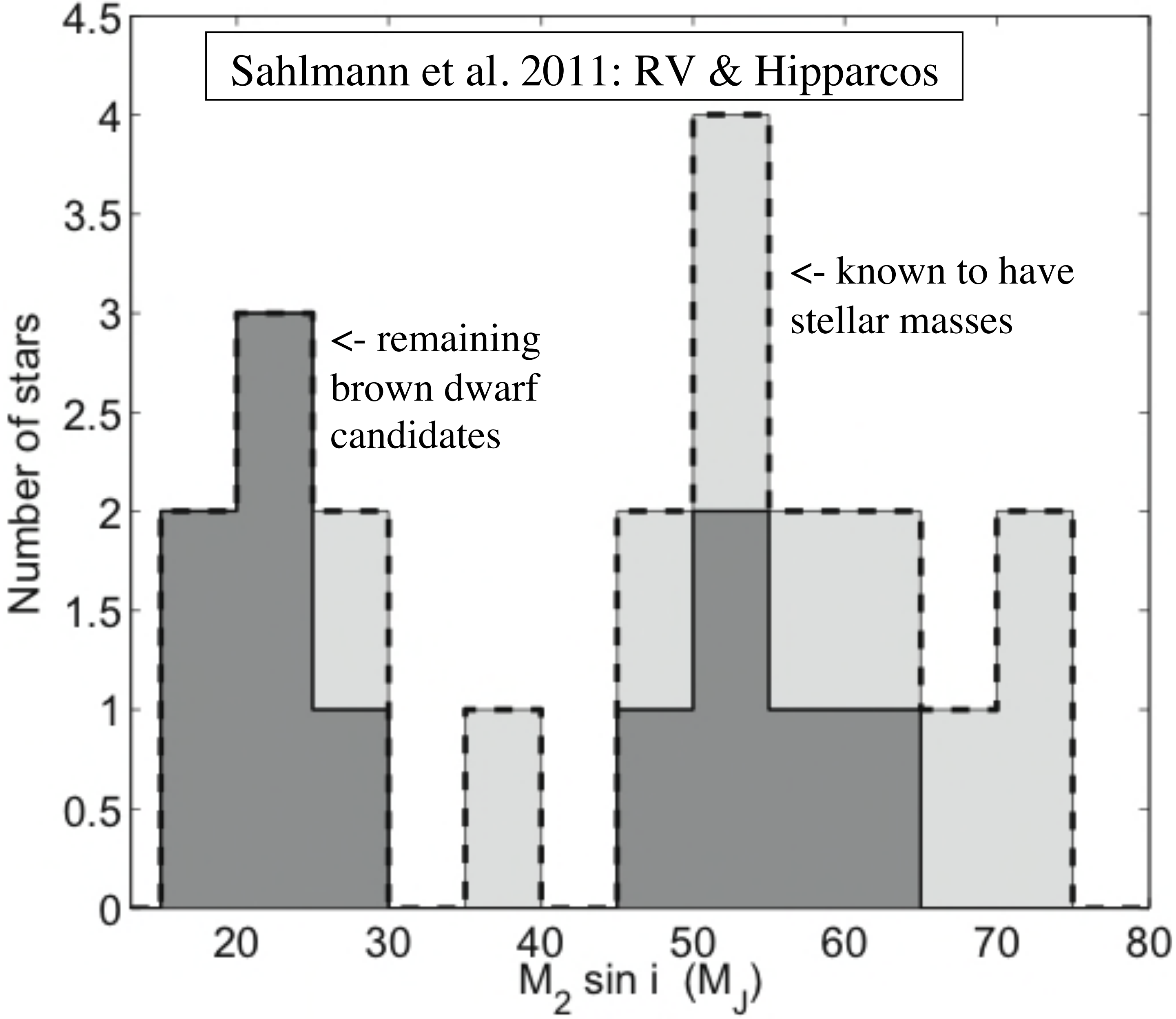
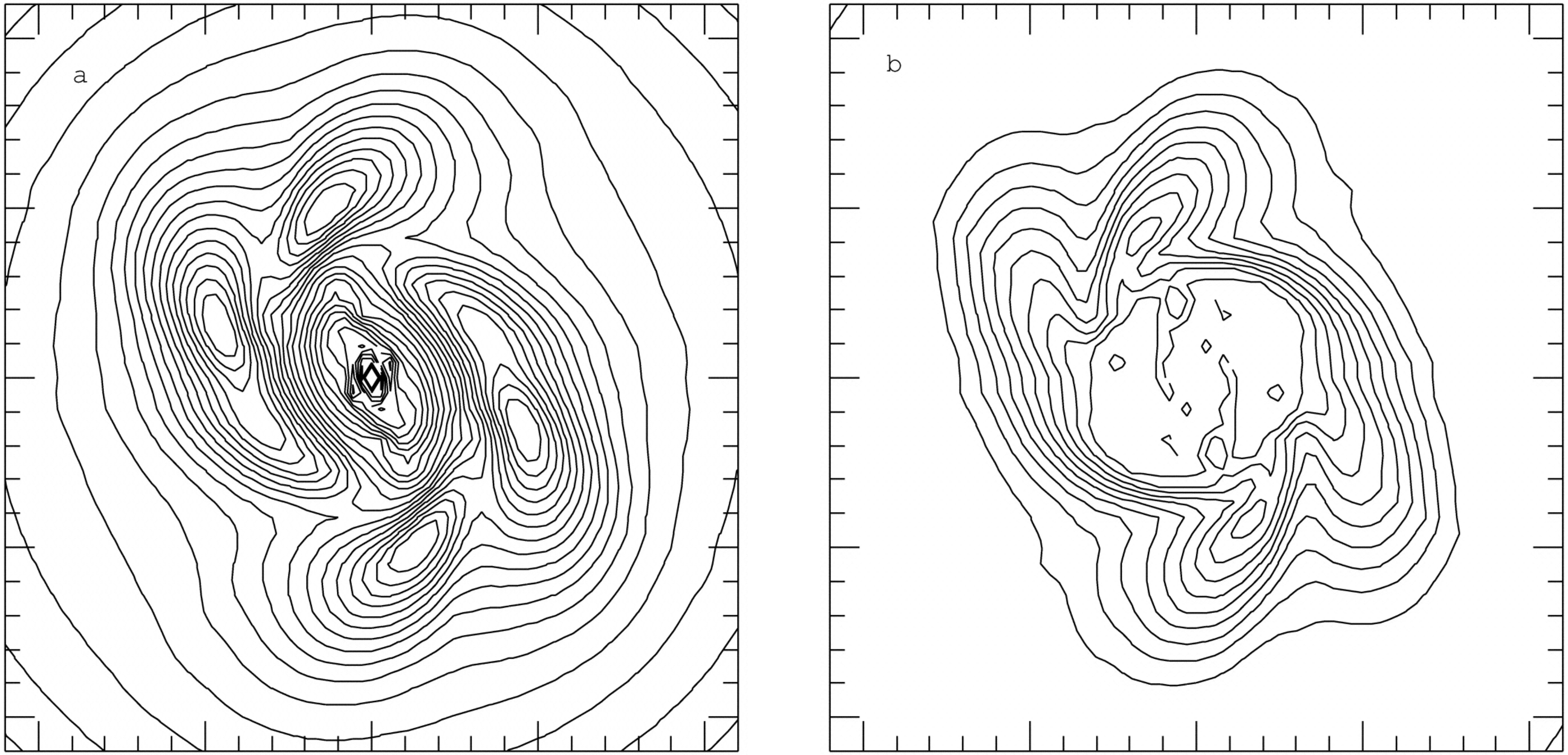

Companions of solar-type stars
Two different mechanisms for binary and planet formation
Udry 2010
Brown-dwarf desert
Planets?
35
30
25
20
15
10
5
N
0.001
0.01
0.1
1
Binaries
Exoplanets
log(m$_2$ sin i) [M$_\odot$]
Halbwachs et al. 2003

brown-dwarf desert vs. planets? (25 M_{Jup}?)



Boss (2001): pseudo-MHD 3D radiative transfer cloud collapse



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)

BOSS AND BODENHEIMER

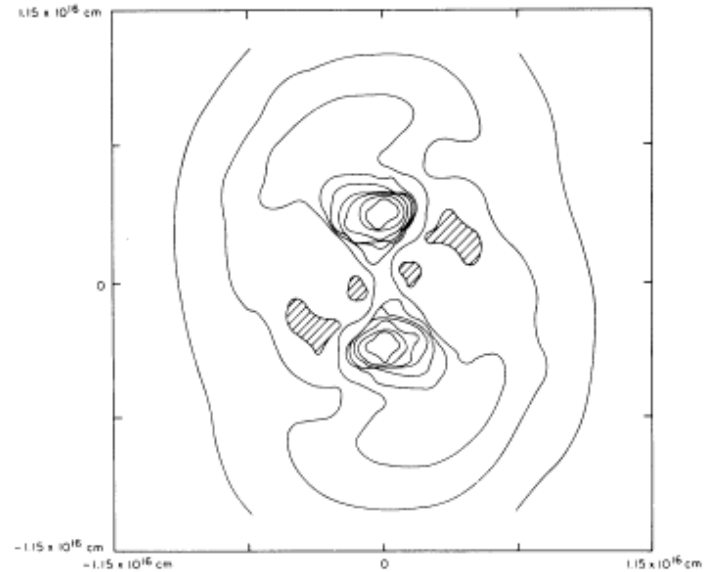


FIG. 4a

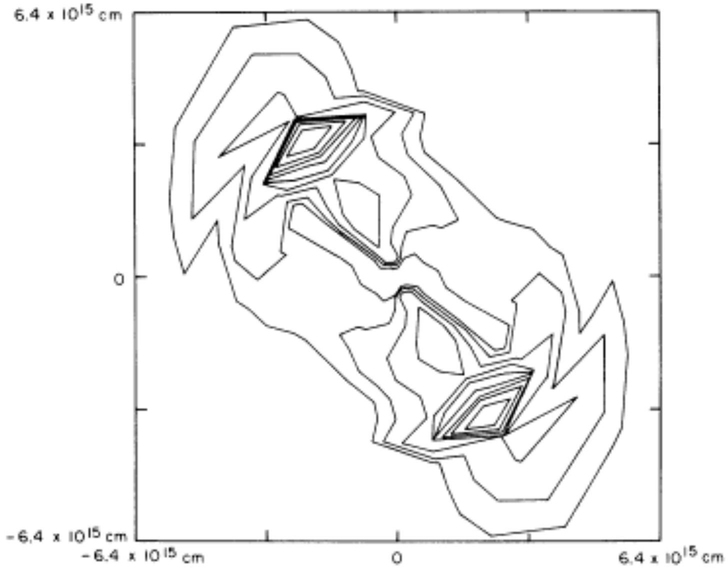
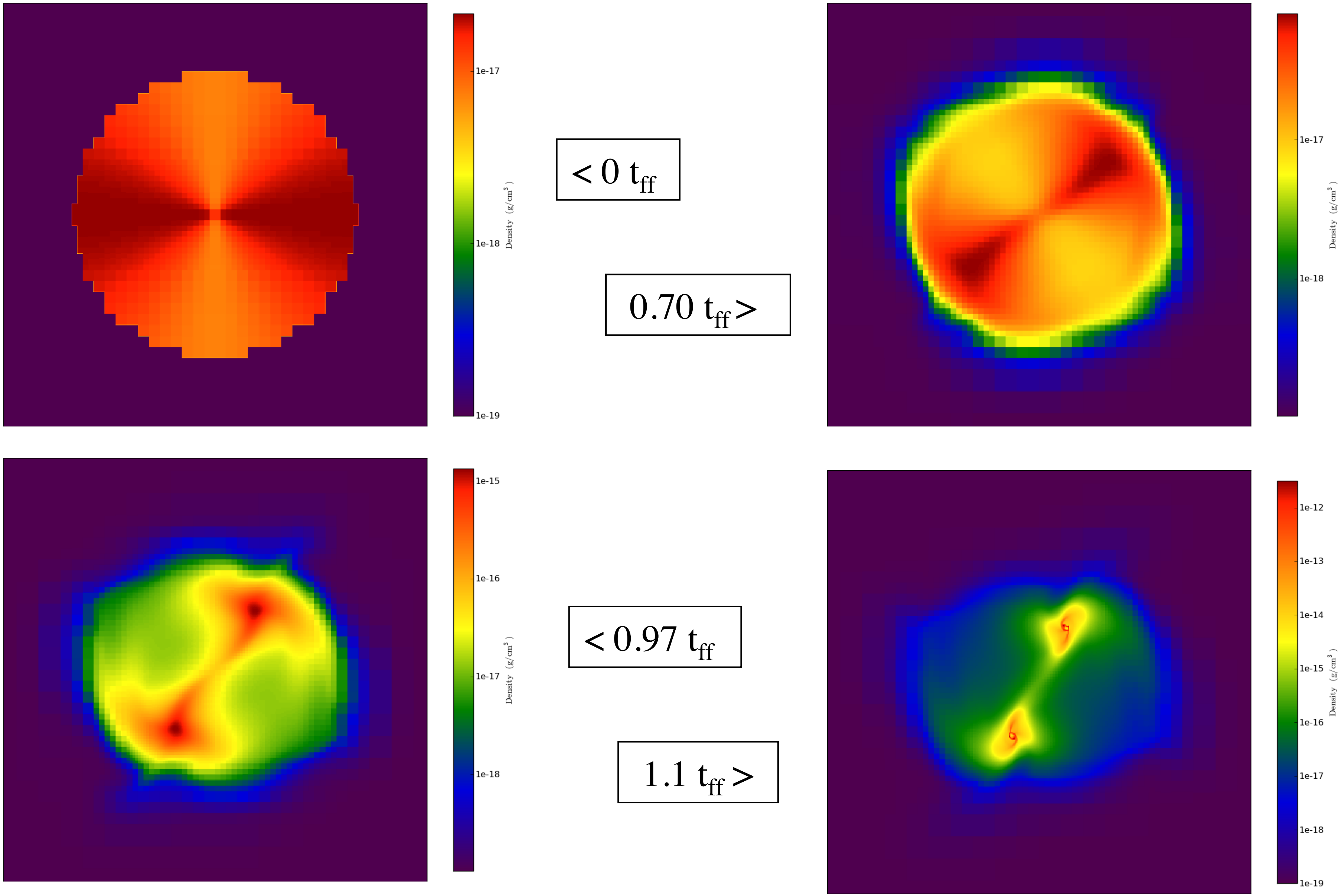


FIG. 4b

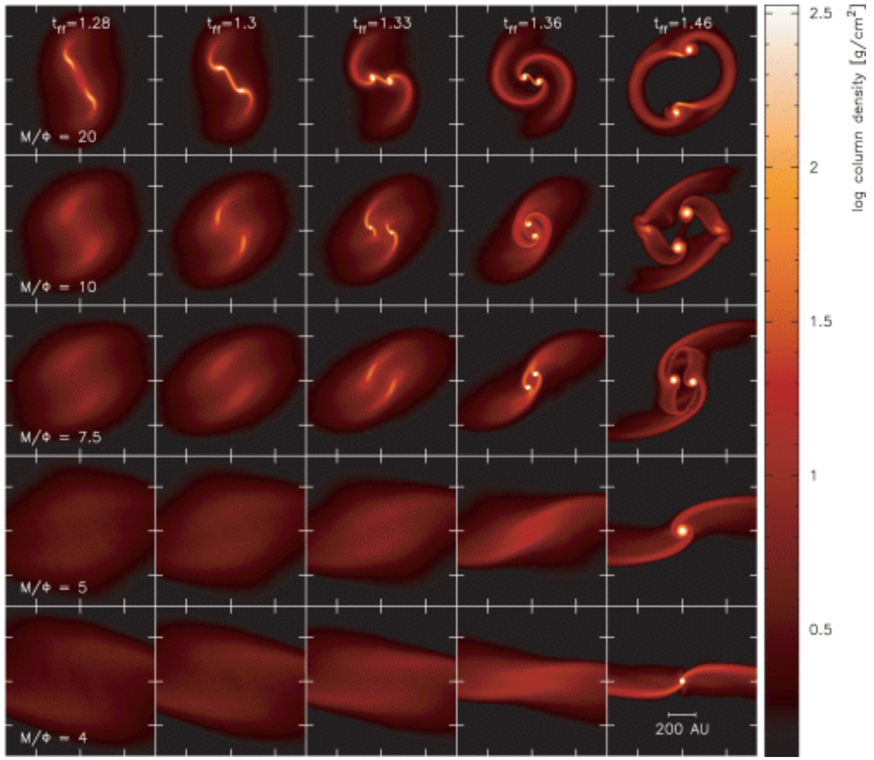
FIG. 4.—(*a*) Equidensity contours in the equatorial plane, showing the inner portion of the cloud as calculated by
2.70 × 10^4 years (1.54 initial free-fall times). *Contour interval:* factor 2.15; *maximum density:* 4.38 × 10^{-13} g cm^{-3}. T

This work: Enzo, B&B isothermal test case, 50% m = 2

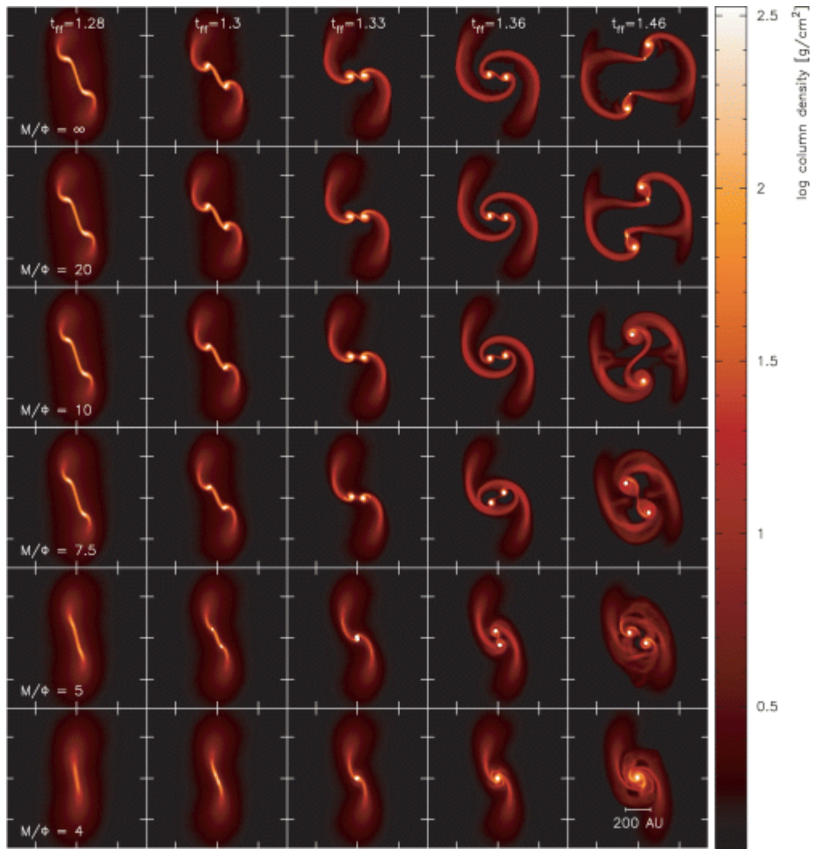


Price & Bate (2007): SPH MHD B&B Test Case (10% m =2)

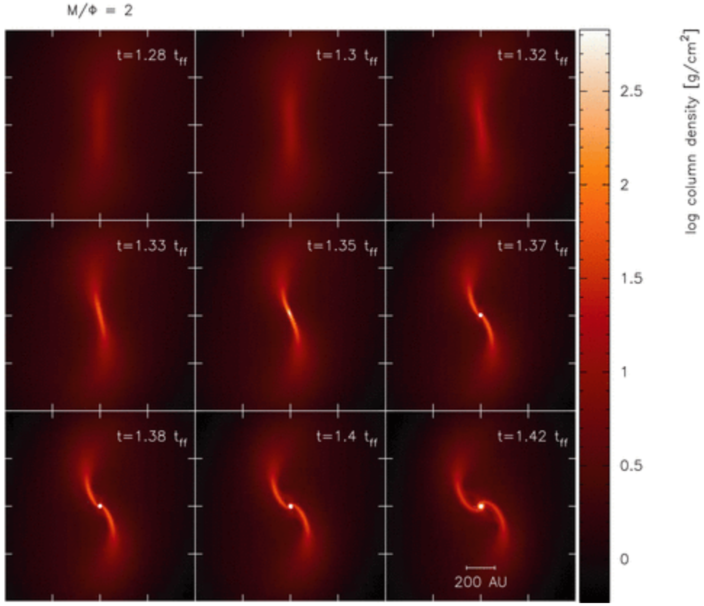
B perpendicular to rotation axis



B parallel to rotation axis

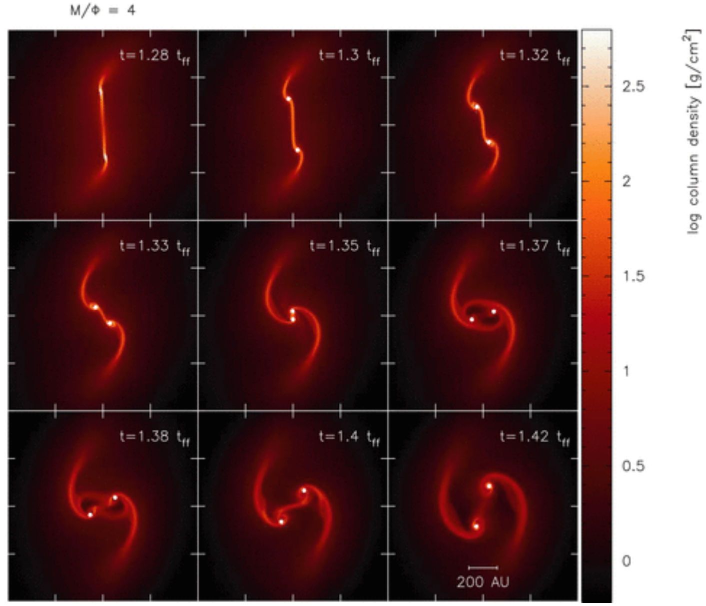


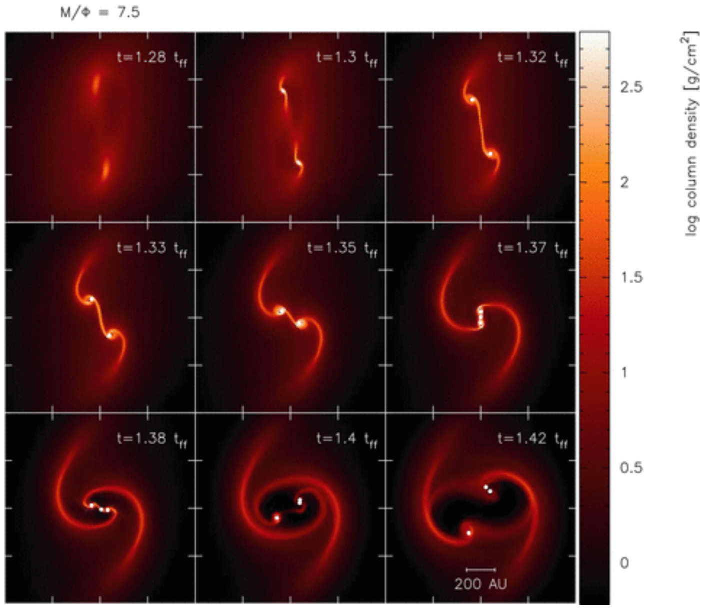
Burzle et al. (2011): SPH, B parallel to rotation axis, 10% m = 2



< B_i = 407 μG

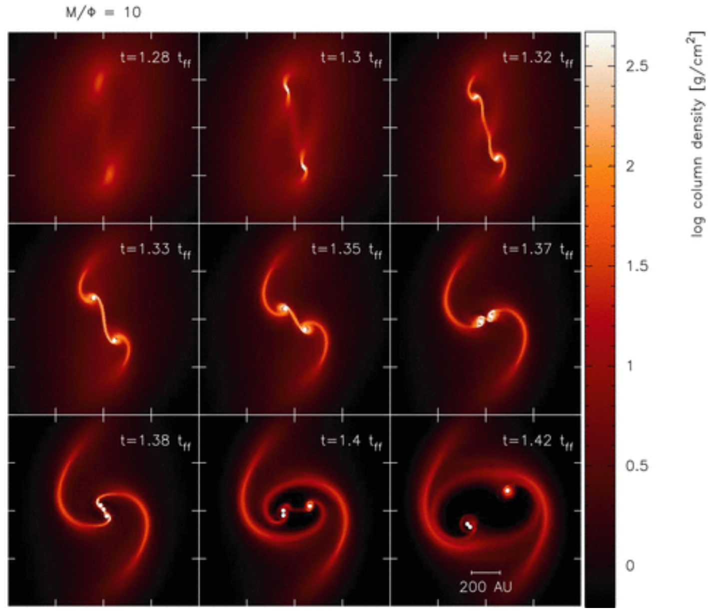
B_i = 203 μG >



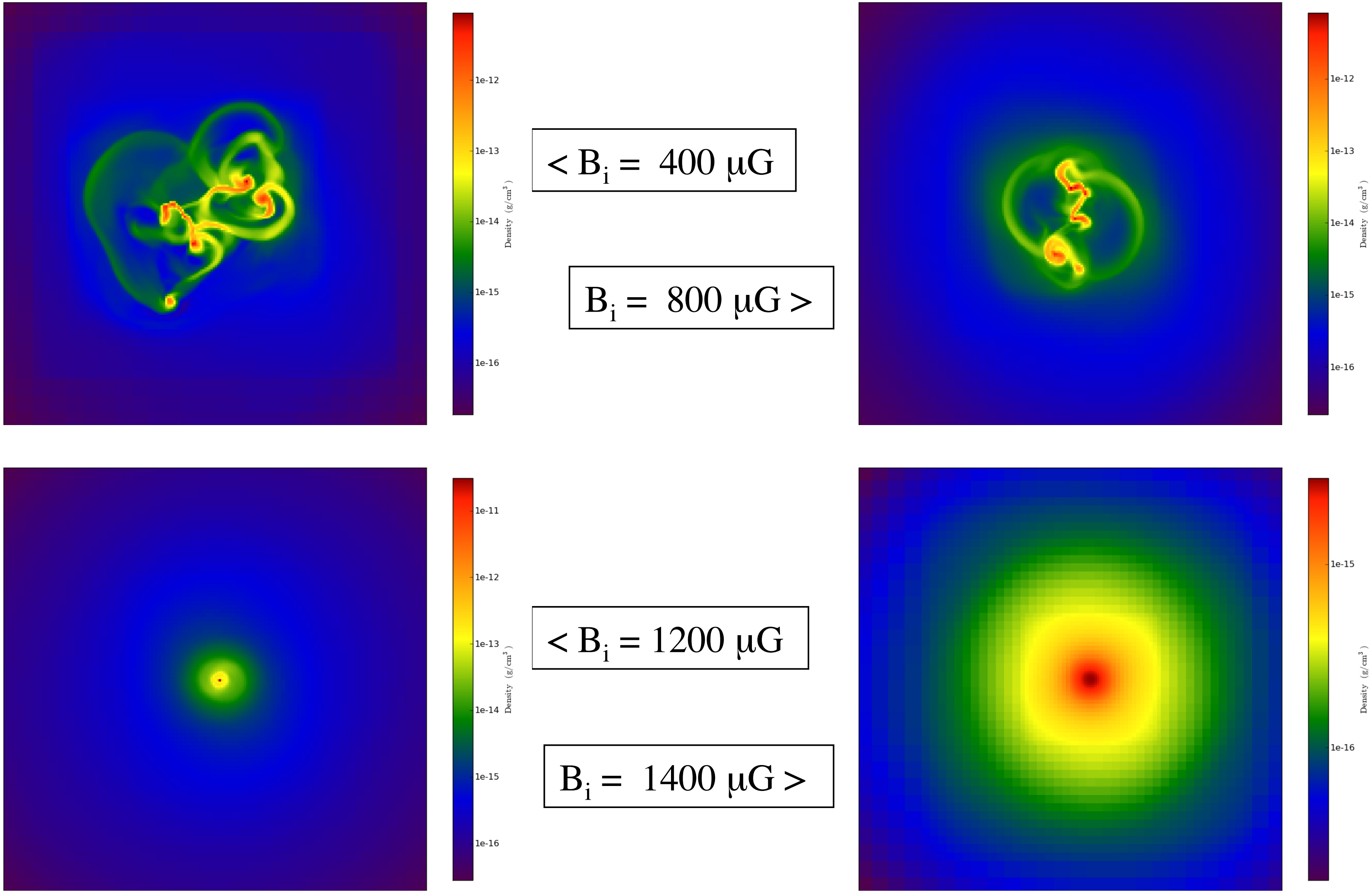


< B_i = 108 μG

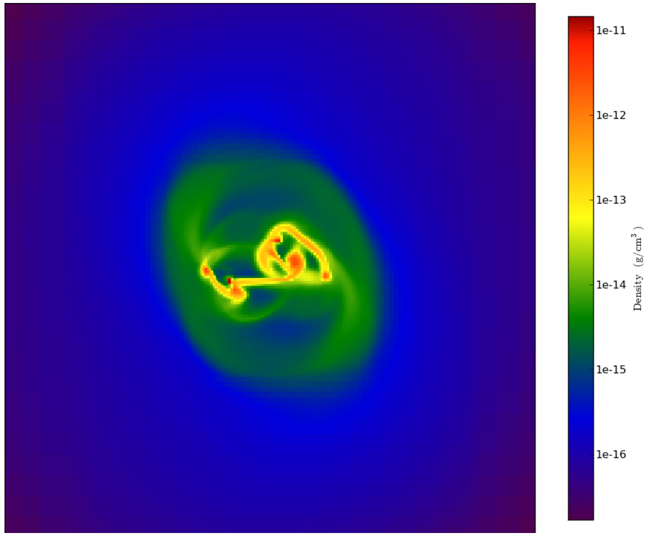
B_i = 81.3 μG >



This work: Enzo, B parallel to rotation axis, 10% m = 2

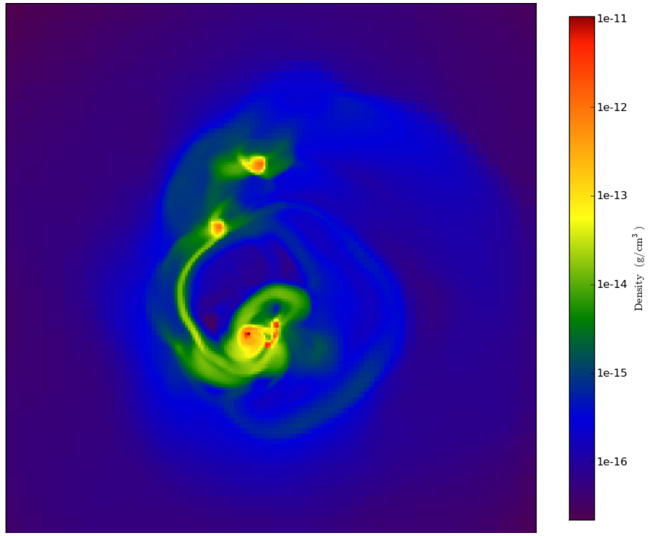


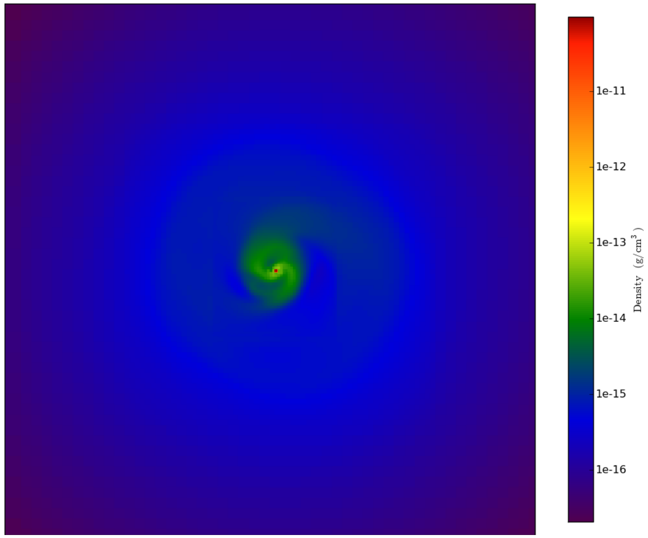
This work: Enzo, B perpendicular to rotation axis, 10% m = 2



< B_i = 400 μG

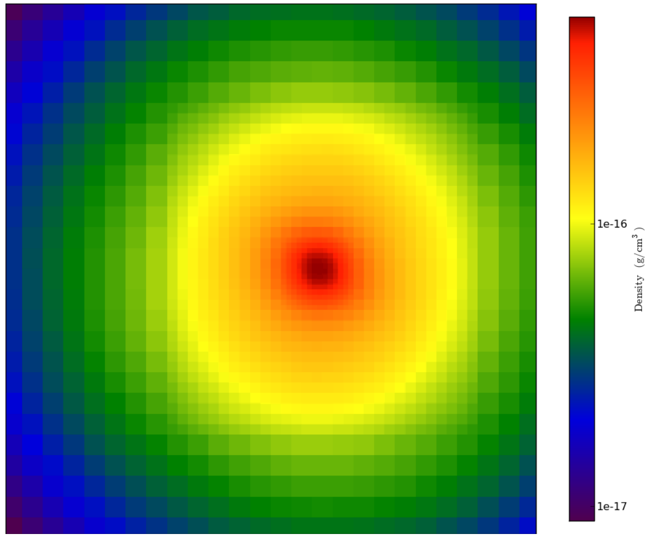
B_i = 1000 μG >



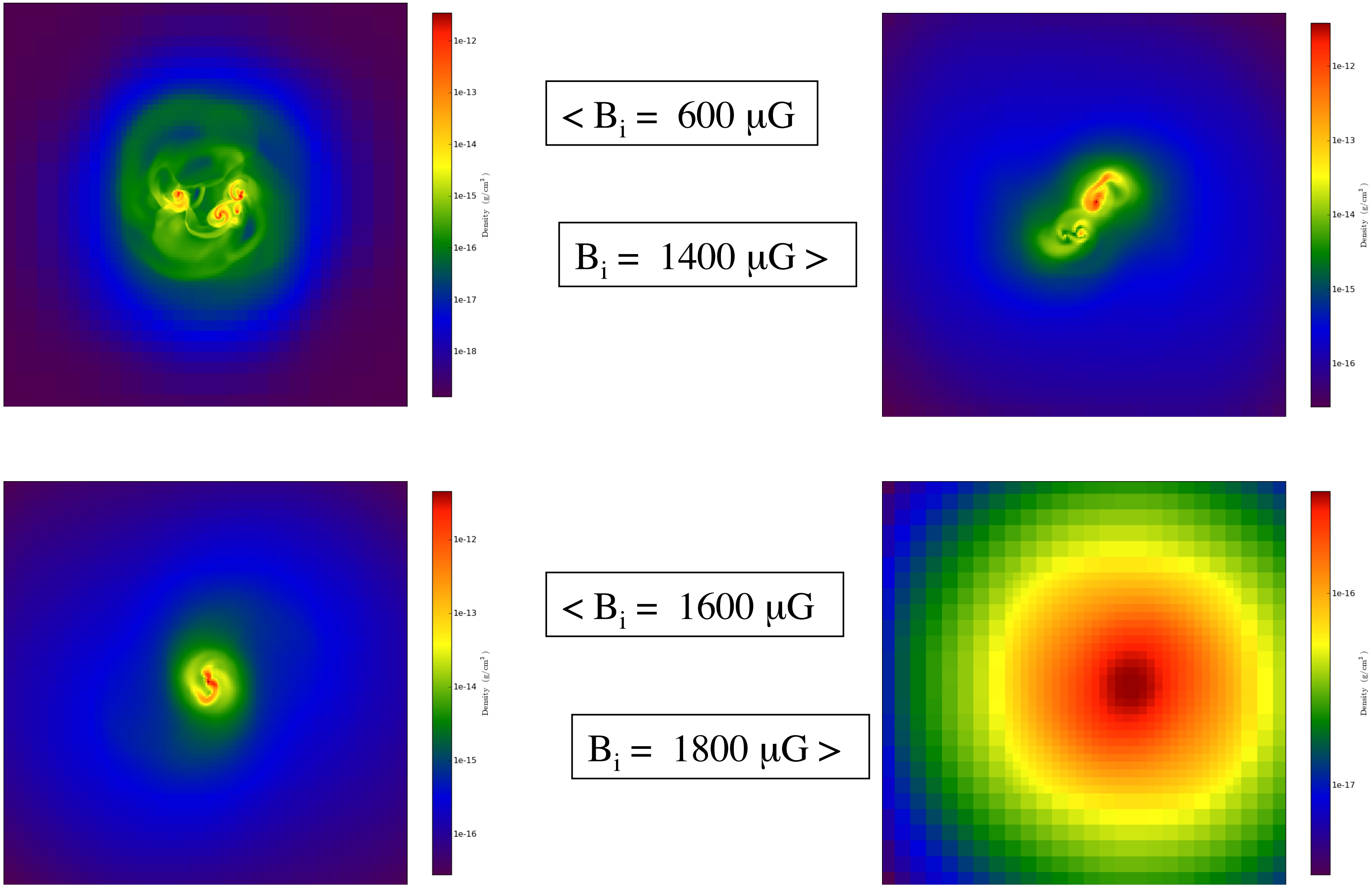


< B_i = 1200 μG

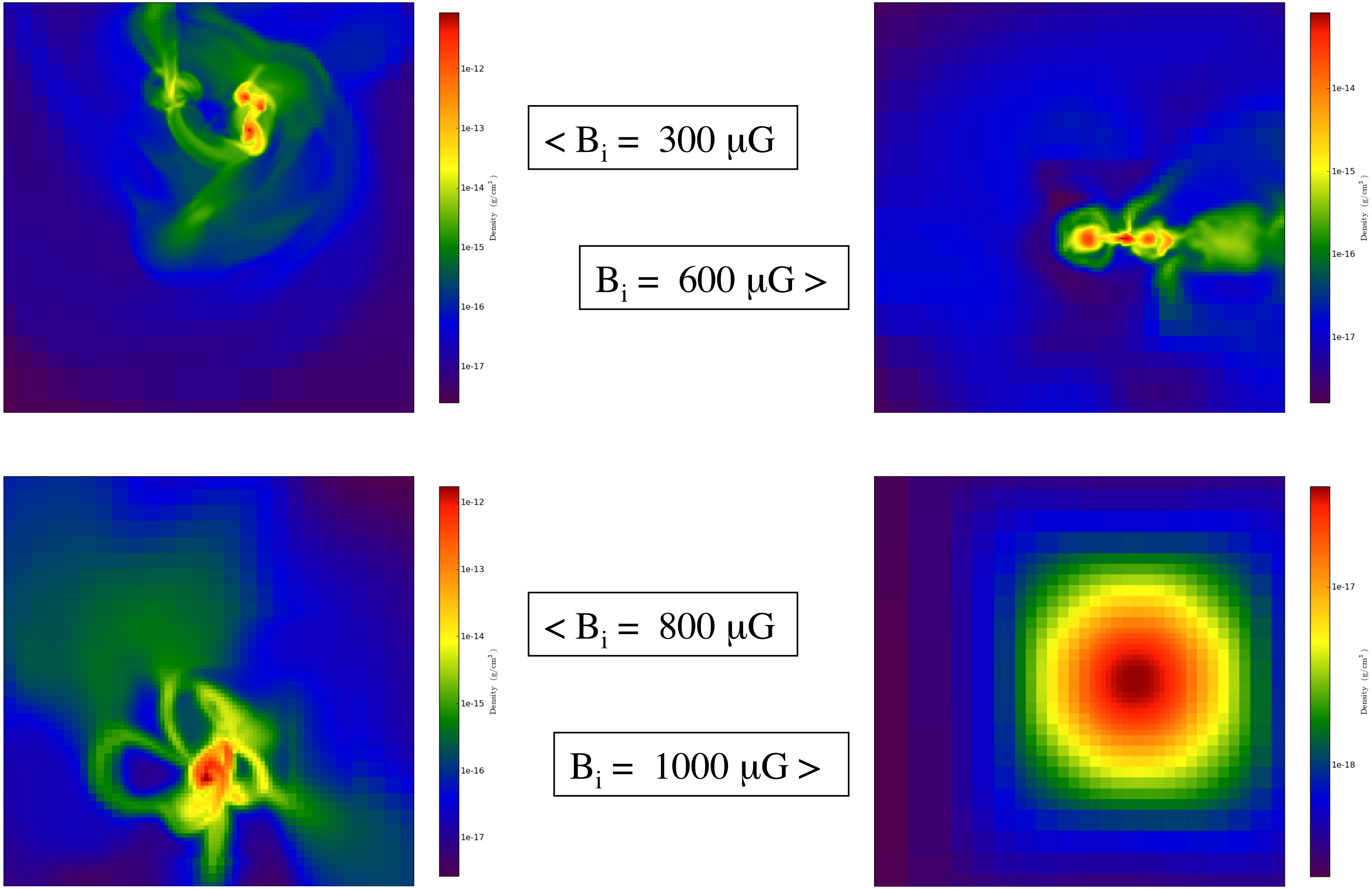
B_i = 1400 μG >



This work: Enzo, B parallel to rotation axis, 50% m = 2



This work: Enzo, B perpendicular to rotation axis, 50% m = 2



Magnetic B&B Test Case Results: 50% m = 2 density perturbations

B specified in microgauss

model name	initial Bx	initial By	initial Bz	result time (t_{ff})	result
mag-x-300	300.0	0.0	0.0	5.8	collapses/fragments
mag-x-600	600.0	0.0	0.0	13.4	collapses/single
mag-x-600	700.0	0.0	0.0	15.6	collapses/single
mag-x-800	800.0	0.0	0.0	8.8	collapse/sing/arms
mag-x-1000	1000.0	0.0	0.0	20.7	little collapse/single
mag-x-1200	1200.0	0.0	0.0	44.0	little collapse/single
mag-z-300	0.0	0.0	300.0	1.8	collapses/fragments
mag-z-600	0.0	0.0	600.0	2.4	collapses/fragments
mag-z-1000	0.0	0.0	1000.0	1.7	collapses/fragments
mag-z-1200	0.0	0.0	1200.0	2.4	collapses/fragments
mag-z-1300	0.0	0.0	1300.0	2.2	collapses/fragments
mag-z-1400	0.0	0.0	1400.0	2.6	collapse/fragments
mag-z-1500	0.0	0.0	1500.0	6.0	collapse/fragments
mag-z-1600	0.0	0.0	1600.0	7.7	collapse/single
mag-z-1800	0.0	0.0	1800.0	9.2	little collapse/single
mag-z-2000	0.0	0.0	2000.0	11.5	little collapse/single

Magnetic B&B Test Case Results: 10% m = 2 density perturbations

B specified in microgauss

model name	initial Bx	initial By	initial Bz	result time (t_{ff})	result
mag-x-400-10	400.0	0.0	0.0	1.8	collapses/fragments
mag-x-600-10	600.0	0.0	0.0	2.2	collapses/fragments
mag-x-800-10	800.0	0.0	0.0	4.4	collapses/fragments
mag-x-1000-10	1000.0	0.0	0.0	3.7	collapses/fragments
mag-x-1100-10	1100.0	0.0	0.0	6.6	collapses/single
mag-x-1200-10	1200.0	0.0	0.0	4.2	collapses/single
mag-x-1400-10	1400.0	0.0	0.0	8.4	little collapse/single
mag-x-1600-10	1600.0	0.0	0.0	7.8	little collapse/single
mag-z-400-10	0.0	0.0	400.0	2.2	collapses/fragments
mag-z-800-10	0.0	0.0	800.0	2.0	collapses/fragments
mag-z-900-10	0.0	0.0	900.0	3.5	collapses/fragments
mag-z-1000-10	0.0	0.0	1000.0	7.3	collapses/fragments
mag-z-1100-10	0.0	0.0	1100.0	9.5	collapse/single
mag-z-1200-10	0.0	0.0	1200.0	3.5	collapses/single
mag-z-1400-10	0.0	0.0	1400.0	7.0	little collapse/single
mag-z-1600-10	0.0	0.0	1600.0	12.8	little collapse/single
mag-z-1800-10	0.0	0.0	1800.0	15.8	little collapse/single

Conclusions for 10% m = 2

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

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

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

- 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

- This work finds a critical value of $B_i < 1800\ \mu G$ for collapse with magnetic field parallel to rotation axis
- This work finds a critical value of $B_i < 1000\ \mu G$ for collapse 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