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Scorpio: A Two-fluid MHD Code for Molecular Cloud Simulations

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Introduction

Scorpio is a two-fluid grid-based finite-volume code. Motivated by our recent detection of the ambipolar-diffusion (AD) scale, 0.4 pc, for cloud turbulence (Tang, Li & Lee 2018), we developed Scorpio for molecular cloud simulations. The ideal magnetohydrodynamic (MHD) assumes flux-freezing, where the fully ionized gas and B-fields are perfectly coupled. However, at the AD scale, the weakly ionized gas shall be handled by non-ideal effect and two-fluid MHD. We will present the applications of Scorpio on AD, from the gravitational collapse of spherical cloud at pc scale, to the AD turbulence at the core scale. At the core scale, turbulence is the source of angular momentum in the protostellar disk, in which the ion-neutral decoupling can stop the magnetic braking.

Method

Based on the Godunov method, the conservation parts of the fluid are solved by approximate Riemann solvers, Harten–Lax–van Leer family HLLC for neutrals and HLLD for ions, combined with a piecewise linear reconstruction (PLM) at the cell interfaces and constrained transport (CT) for preserving $\nabla \cdot B = 0$. For the source terms, the self-gravity is solved using Fast Fourier Transformation method (FFT). The AD source term is integrated using a second-order semi-implicit method, trapezoidal rule backward-difference formula (TR-BDF2) (Tilley et al. 2012).

We show the momentum equations of ions and neutrals, coupled by the AD collision term.

The computation is expensive due to the low ionization fraction of ions and neutrals $R = \frac{n_i}{n_i + n_n}$. The drag coefficient is $\alpha = \frac{<\sigma_{in} v>}{m_i + m_n}$ (Draine et al. 1983).

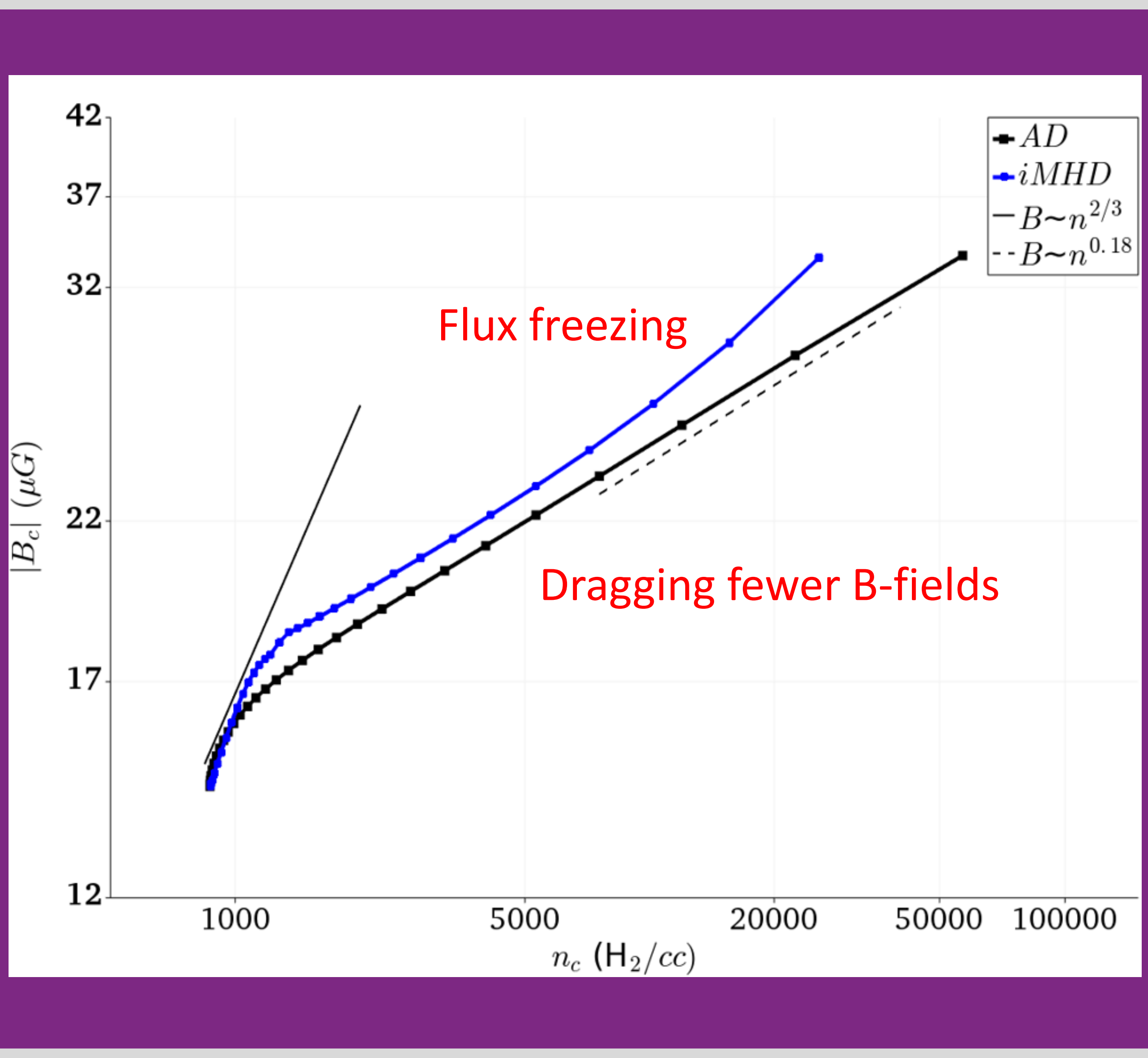
$$\frac{\partial(\rho_n v_n)}{\partial t} + \nabla \cdot (\rho_n v_n v_n) + \nabla P_n = -\rho_n \nabla\Phi - \alpha \rho_n \rho_i (v_n - v_i)$$

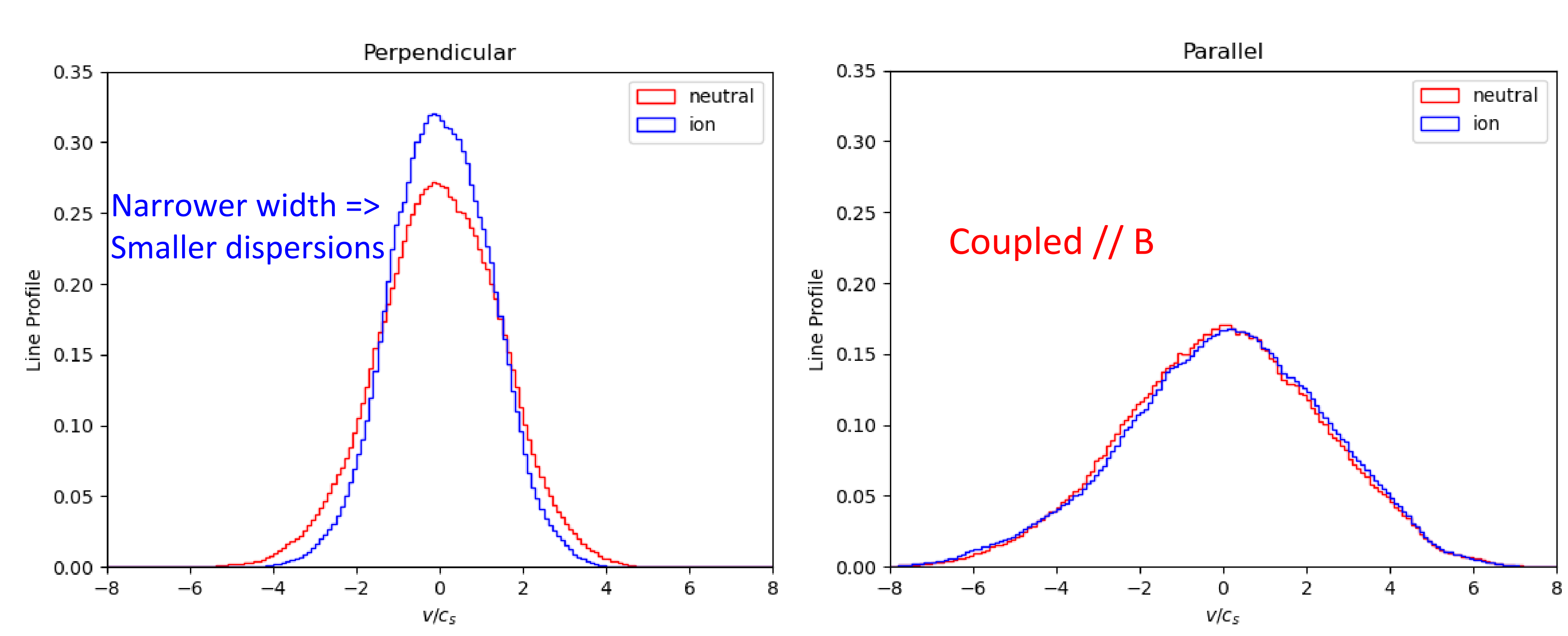
$$\frac{\partial(\rho_i v_i)}{\partial t} + \nabla \cdot (\rho_i v_i v_i - BB) + \nabla\left(P_i + \frac{1}{2}|B|^2\right) = -\rho_i \nabla\Phi - \alpha \rho_n \rho_i (v_i - v_n)$$

B-n relations

We set up a 3D "near-Bonner-Ebert" (Myers 2008) isothermal spherical core of 2 pc to regulate the collapse, embedded in a uniform background cloud density. The uniform $|B| = 14.5\ \mu\mathrm{G}$ is set along z-direction, initial central density $\sim 900\ \mathrm{cm}^{-3}$ and ionization fraction $\mathrm{R} \sim 10^{-4}$.

Figure shows B-n relations at the mass center between ideal MHD and AD models. Both cases show a 2/3 slope at the very beginning for an initially super-critical, $\lambda = 1.5$, isolated spherical cloud. Both the slopes deviate from the 2/3 and flatten due to the stronger magnetic forces from the compressed field lines. For ideal MHD, flux freezing is assumed that B-fields follow the gas flow tightly during gravitational collapse. For AD, the neutrals feel the Lorentz force indirectly through the collisions with ions. The neutral gas collapses with dragging fewer B-fields. Hence, for AD, B increases with n measured at the center slower than the case of ideal MHD.

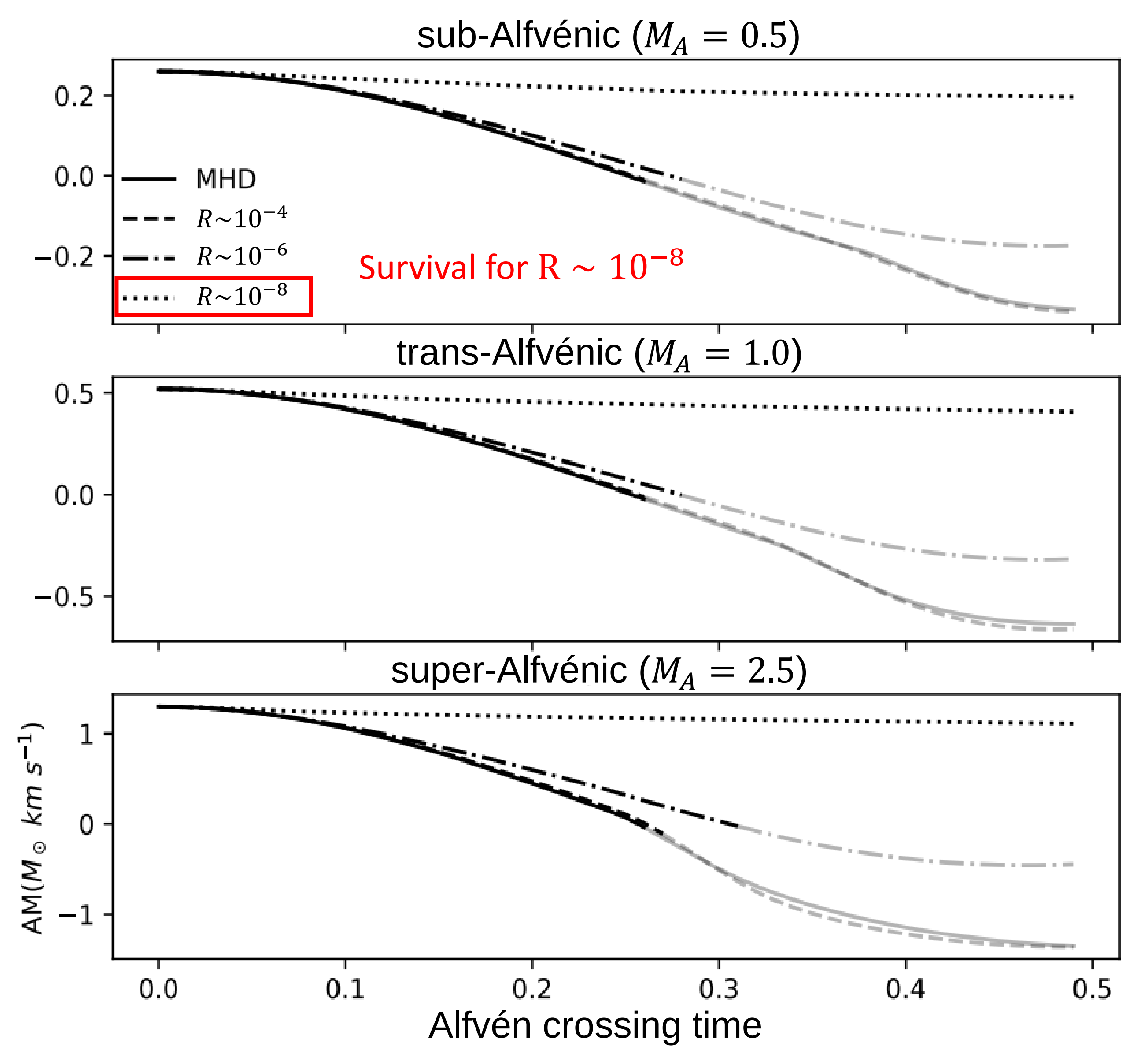




Turbulence-Induced AD

Below AD scale $L_{AD} = B^2/4\pi\alpha\rho_i\rho_n v$, the ion-neutral friction damps the turbulence of ions strongly due to the low ionization ratio R. However, ions are constrained by the magnetic fields to move perpendicularly due the Lorentz force, but the neutrals are not. The small neutral eddies are fed by their own turbulence cascade and decouple from ions.

Motivated by the observations (Li & Houde 2008; Tang, Li & Lee 2018), we set up a 3D supersonic and sub-Alfvénic turbulence simulation with realistic ionization fraction $\mathrm{R} \sim 10^{-7}$. Results show the synthetic emission lines of ions and neutrals. For parallel LOS, the motions of ions and neutrals along the B-fields are well coupled. For perpendicular LOS, the width of ions is narrower since the velocity dispersions of ions are smaller.



Magnetic Braking

The turbulence can only be trans- to slightly super-Alfvénic in the cloud cores (Zhang et al. 2019), so as the only source of angular momentum in a protostellar disk. The angular momentum in the disk should be soon consumed by magnetic forces if flux-freezing assumption holds, as indicated by the solid lines. We set up a 2D simulation at 0.1 pc with AD under different ionization fractions R and Alfvénic Mach M_A, with total number density $10^5\ \mathrm{cm}^{-3}$. The uniform $|B| = 1\ \mathrm{mG}$ is set along x-direction. The velocity perturbation in y-direction is initialized to be sinusoidal to represent the turbulence eddies. Hence, an oscillation of the B-field lines can reverse the velocity fields by the Lorentz forces of ions.

Results show the the angular momentum can survive, indicated by positive curve, especially under realistic $\mathrm{R} \sim 10^{-8}$ due to weak coupling of neutrals and ions/B-fields. The grey part of each curve indicates the negative angular momentum, because gravity is absent in the simulation.

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