Parameter Dependence of Ambipolar Diffusion Effects in Alfvén-Wave-Driven Stellar Winds

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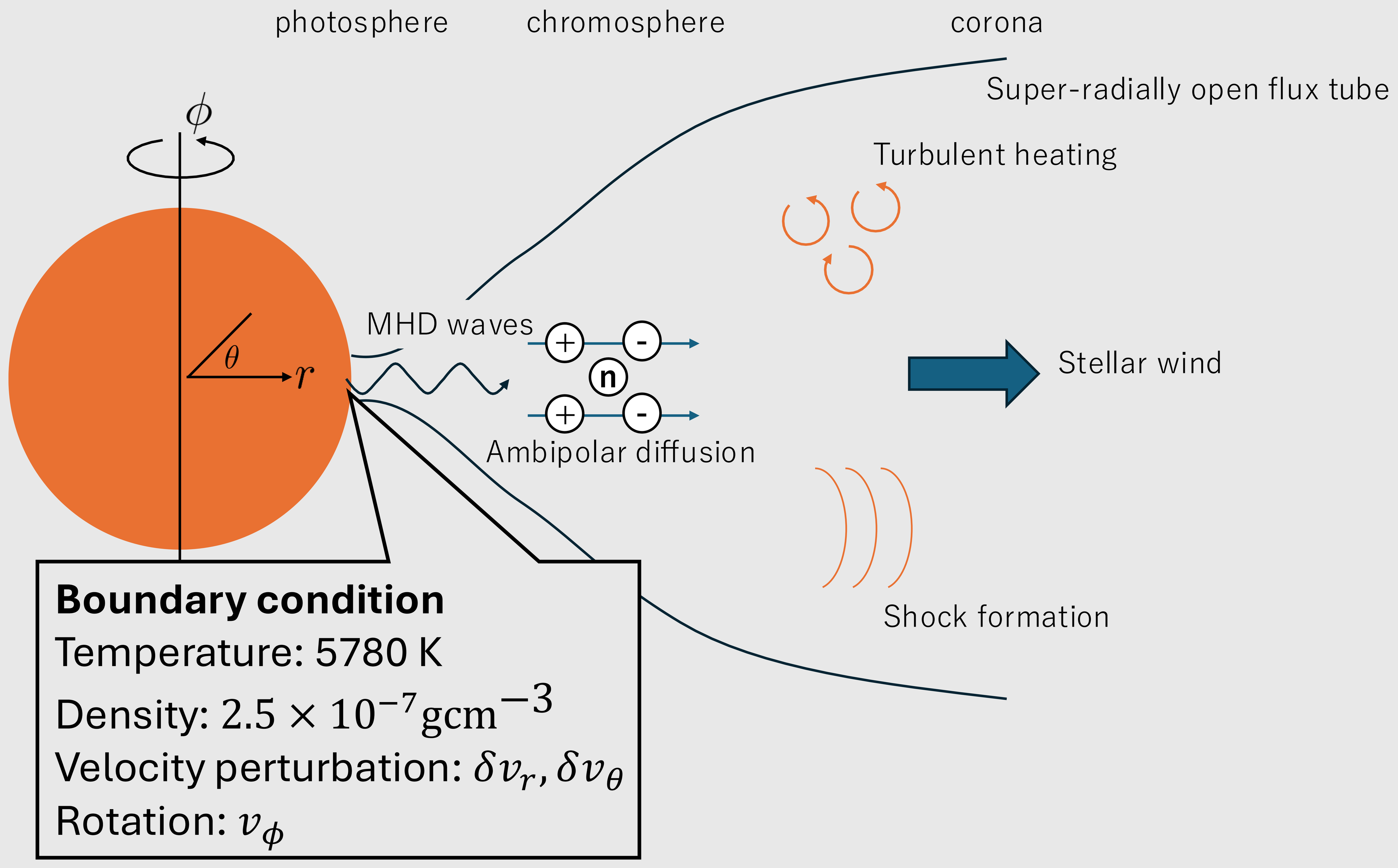
Background & Motivations

- Mass-loss rate and torque are key quantities in stellar wind.
- Shoda et al. (2020) investigated how stellar rotation affects the mass-loss rate and torque with Alfvén-wave-driven model.
- However, their model does not include ambipolar diffusion, which possibly significant role for solar-like stellar winds (Matsuoka et al. (2024)).
- In this study, we perform stellar wind simulations that include both rotation and ambipolar diffusion, and investigate the parameter dependence of the mass-loss rate and torque over a wide parameter range.



Methods

- Equations: nonideal 1D-MHD simulation
  - Ohm & ambipolar diffusion included
  - Flux tube model (Kopp & Holzer 1976, Suzuki et al. 2013)
  - Heat conduction, radiation (Suzuki 2018), phenomenological turbulent dissipation (Hossain et al. 1995, Shoda et al. 2018) included
- Simulation region:
  Photosphere to wind region (outermost: r ~ 30-70 $R_\odot$)
- Changing input parameters:
  B_0: Radial magnetic field
  f_0: Filling factor
  $\delta v_r, \delta v_\theta$: Velocity perturbation
  Ω_*: Rotation rate

Ohmic and ambipolar diffusion

$$\eta_O = \frac{c^2 m_e \nu_{en}}{4\pi e_c^2 n_e} \simeq 2.3 \times 10^2 \frac{\max((1-x_e),0)}{x_e}\sqrt{\frac{T}{\mathrm{K}}}\,\mathrm{cm^2\,s^{-1}}$$

$$\eta_{AD} = \frac{B^2(\rho_n/\rho)^2}{4\pi\chi\rho_i\rho_n} \simeq 2.1 \times 10^{-16}\frac{(B/\mathrm{G})^2\max((1-x_e),0)^2}{[\rho/(\mathrm{g\,cm^{-3}})]^2 x_e}\,\mathrm{cm^2\,s^{-1}}$$

m_e: electron mass, e_c: elementary charge
ν_{en}: collision frequency between electron and neutral species
$\chi = \overline{\sigma_{in}\nu_{in}}/(m_i + m_n)$

Model examples

Model	diffusion	B_0 (kG)
I1	off	1.41
D1	on	1.41
I2	off	2.82
D2	on	2.82

* Other 184 cases are also simulated.

Other parameters:
$f_0 = 1/1265$
$\delta v_r = \delta v_\theta = 1.0\,\mathrm{km/s}$
$\Omega_* = 2.9 \times 10^{-6}\,\mathrm{rad/s}$
(Period ~ 25 day)

Results & Discussions

- Scaling laws of mass loss rate and torque

$$\dot M_{\rm ideal} = 2.09\times10^{-14}\times\left(\frac{\delta v}{1\,\mathrm{km\,s^{-1}}}\right)^{3.23}\times\left(\frac{B_0}{1\,\mathrm{kG}}\right)^{-0.0763}\times\left(\frac{f_0}{7.91\times10^{-4}}\right)^{0.468}\times\left(\frac{\Omega}{\Omega_\odot}\right)^{0.0171} M_\odot\,\mathrm{yr^{-1}}$$

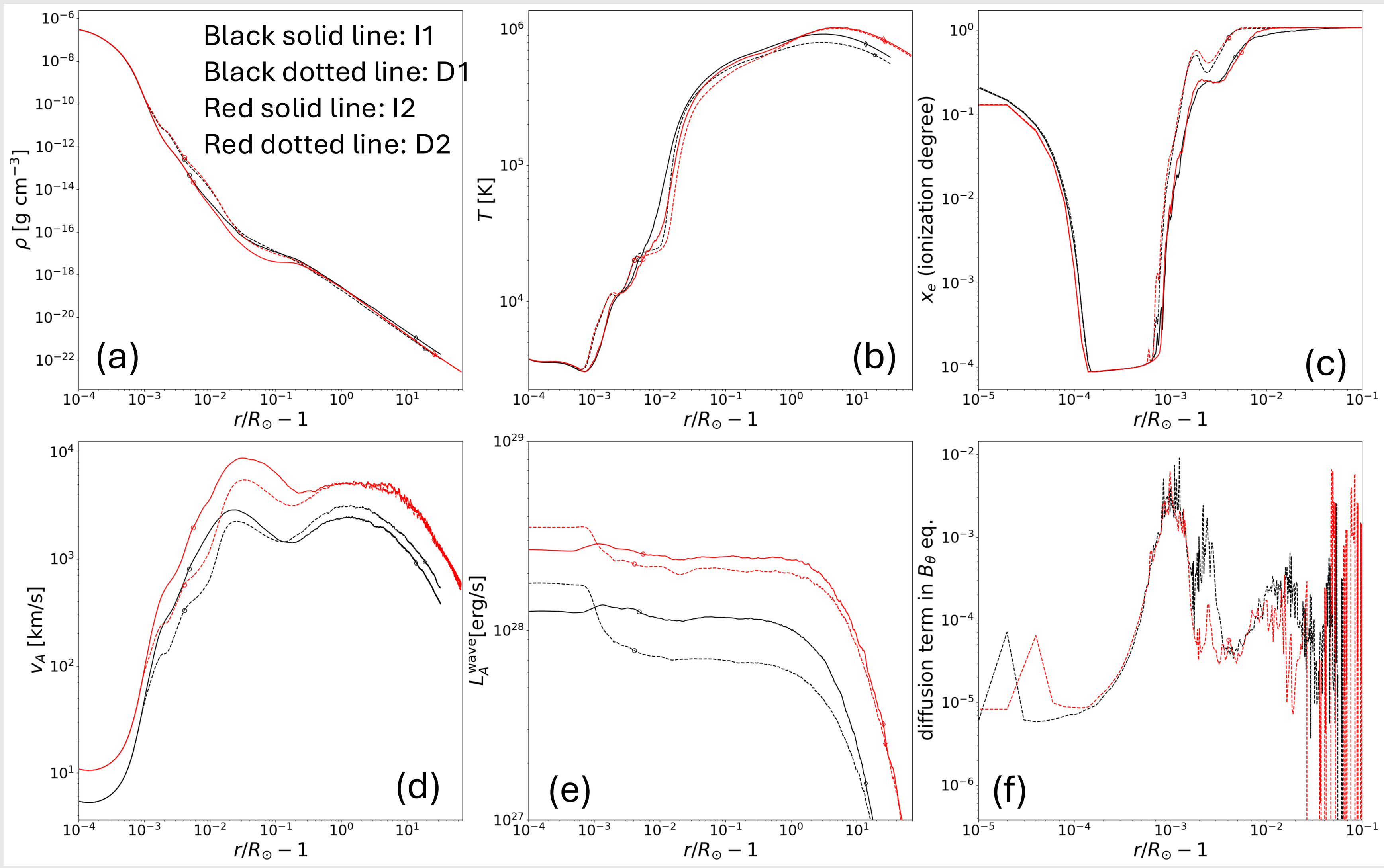
$$\dot M_{\rm diff} = 0.917\times10^{-14}\times\left(\frac{\delta v}{1\,\mathrm{km\,s^{-1}}}\right)^{3.87}\times\left(\frac{B_0}{1\,\mathrm{kG}}\right)^{0.564}\times\left(\frac{f_0}{7.91\times10^{-4}}\right)^{0.742}\times\left(\frac{\Omega}{\Omega_\odot}\right)^{0.0280} M_\odot\,\mathrm{yr^{-1}}$$

$$\tau_{\rm ideal} = 1.88\times10^{30}\times\left(\frac{\delta v}{1\,\mathrm{km\,s^{-1}}}\right)^{0.220}\times\left(\frac{B_0}{1\,\mathrm{kG}}\times\frac{f_0}{7.91\times10^{-4}}\right)^{1.47}\times\left(\frac{\Omega}{\Omega_\odot}\right)^{0.921}\,\mathrm{erg}$$

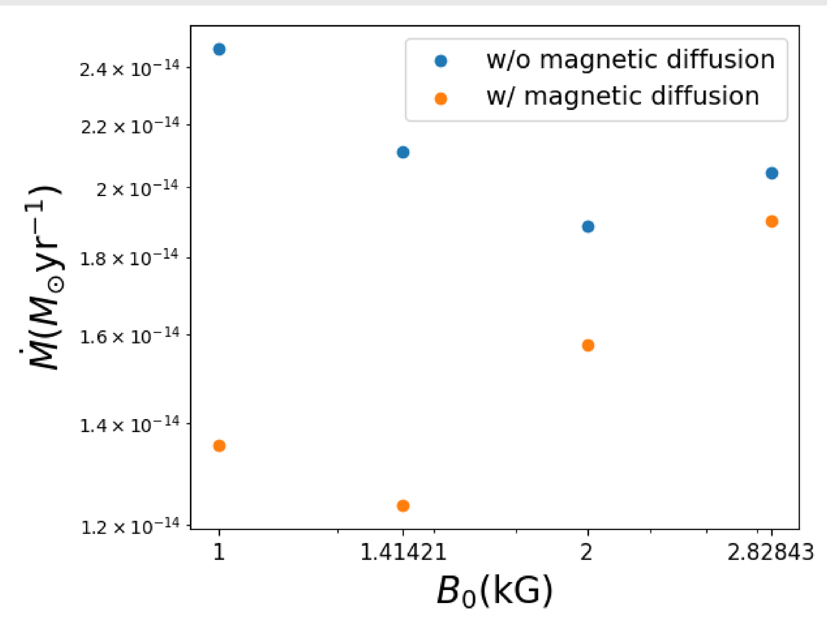
$$\tau_{\rm diff} = 1.97\times10^{30}\times\left(\frac{\delta v}{1\,\mathrm{km\,s^{-1}}}\right)^{0.176}\times\left(\frac{B_0}{1\,\mathrm{kG}}\times\frac{f_0}{7.91\times10^{-4}}\right)^{1.44}\times\left(\frac{\Omega}{\Omega_\odot}\right)^{0.910}\,\mathrm{erg}$$

- Mass-loss rate:
  w/o ambipolar diffusion → independent of B_0
  w/ ambipolar diffusion → dependent on B_0
  - B_0 ↑ → l_{AW} ↑ → ambipolar ↓
    (l_{AW}: the spatial scale of Alfvén waves)
  - B_0 ↑ → v_A ↑ → τ_A ↓
    (τ_A: time that waves are exposed to ambipolar diffusion)
  - The magnitude of the diffusion term depends only weakly on the magnetic field strength.
- Torque: independent of ambipolar diffusion
  - Ambipolar diffusion → $\dot M$ ↓, r_A ↑
    → Ambipolar diffusion little change the torque

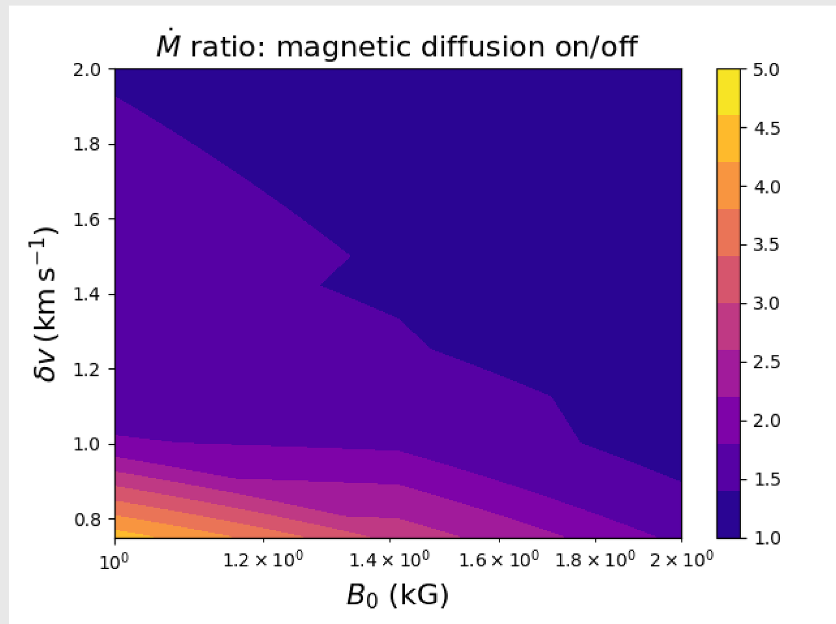
$$\tau_{\rm w} \sim \dot M r_A^2 \Omega_* \quad (\tau_{\rm w}:\ \text{torque})$$



Radial profiles of (a) density, (b) temperature, (c) ionization degree, (d) Alfvén velocity, (e) Alfvén luminosity, (f) rms of diffusion term in induction equation in θ direction



Mass loss rates in cases with/without magnetic diffusion under various magnitude of the magnetic field



Ratio of the mass-loss rate with magnetic diffusion to that without magnetic diffusion

Summary

- We simulated 1D-MHD simulation over wide parameter range.
- Our results suggest that ambipolar diffusion plays an important role only when magnetic field is weak.
- Scaling laws for the mass-loss rate and torque are also derived for both the ideal and ambipolar-diffusion cases.

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