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MAGNETIC BRAKING OF COOL STARS: DEPENDENCE ON CORONAL TEMPERATURE.

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Abstract

- Sun-like and later-type stars possess high temperature coronae and lose mass in the form of stellar winds, driven by thermal pressure and complex magnetohydronamic processes.
- The magnetized outflows of those stars do not significantly affect the structural evolution on the main-sequence, but they brake the stellar rotation by removing angular momentum, a mechanism known as ***magnetic braking***.
- Previous studies (Matt & Pudritz 2008, ApJ, 678, 1109M; Matt et al. 2012, ApJ, 754L, 26M; Réville et al. 2015, ApJ, 798, 116R) have shown how the magnetic braking torque depends on magnetic field strength and geometry, stellar mass, radius and mass loss rate, as well as the rotation rate of the star, assuming a fixed coronal temperature.
- For our study, we explore how different coronal temperatures can influence the spin-down torque, by using MHD simulations of stellar winds (computed with PLUTO code).
- We show that a hotter wind leads to a faster acceleration, and this results to a weaker torque on the star.
- We derive new predictive torque formulae for each coronal temperature.

Simulation Method and Parameter Study

Method: We employ 2.5D, axisymmetric, ideal MHD simulations, using the PLUTO code, to obtain steady-state stellar wind solutions. We consider thermal-pressure-driven (Parker) winds from rotating stars with dipolar magnetic fields.

Aims: Since we adopt a Parker-like wind, coronal temperature is the key parameter determining the velocity and acceleration profile of the flow. For our study we explore how different coronal temperatures can influence the spin-down torque.

Parameter Study: We completed 30 simulations and our parameter space includes variations in **stellar coronal temperature** and **surface magnetic field strength.**

Varied Wind Parameters (dimensionless):

$$\frac{c_s}{v_{esc}} = \frac{(\gamma P_*/\rho_*)^{1/2}}{(2GM_*/R_*)^{1/2}}$$

The ratio of the sound speed to the gravitational escape speed.

$$\Upsilon \equiv \frac{B_*^2 R_*^2}{\dot{M}_w \, v_{esc}}$$

Wind Magnetization: Strength of magnetic field compared to gravity.

Fixed Wind Parameters:

The stellar spin rate, *f*, was fixed at the solar value and the polytropic gas index, (the ratio of specific heats), was fixed at $\gamma = 1.05$.

2.5D Steady-State Wind Solution from Rotating Star with Dipolar Field

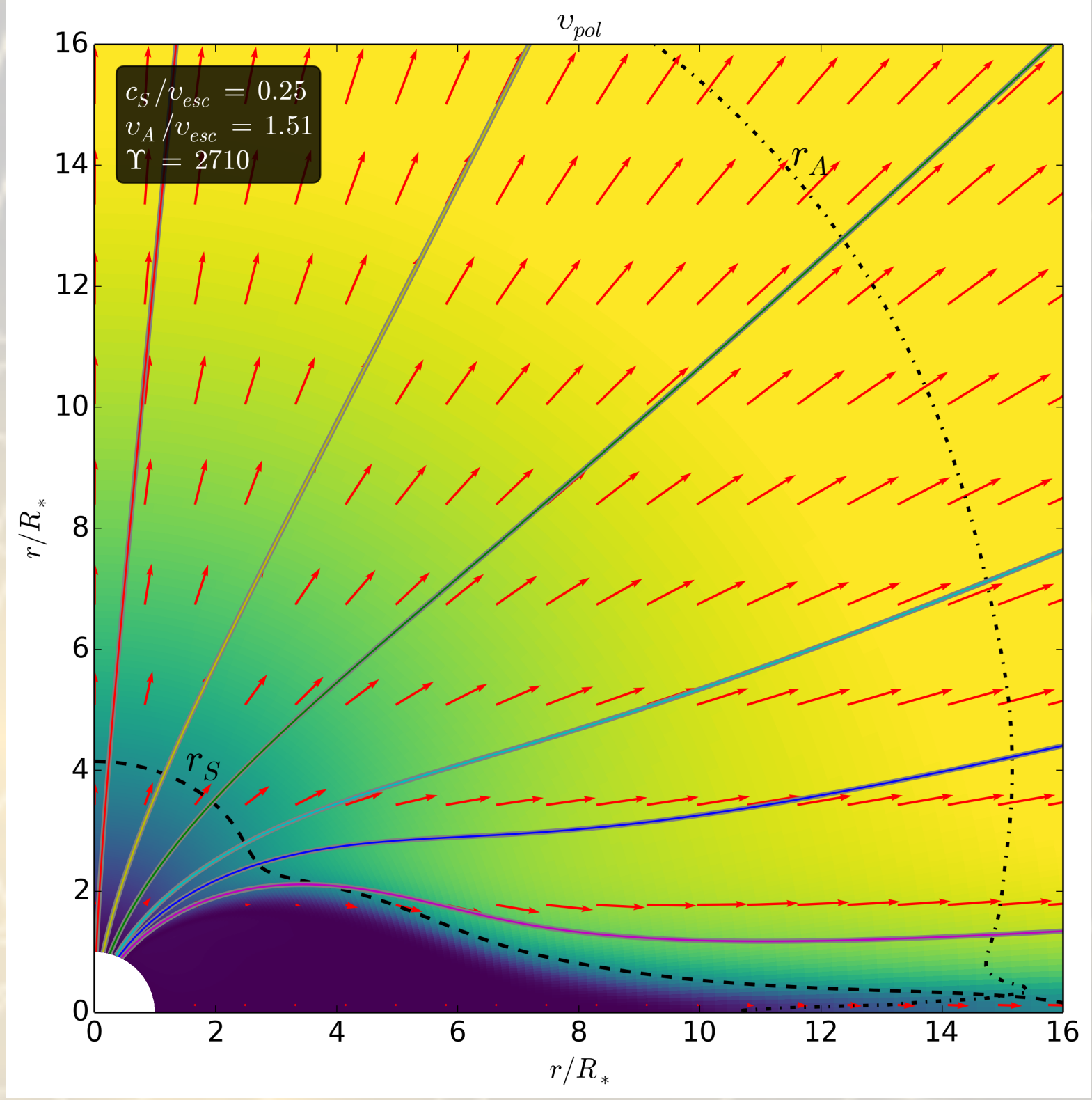


Figure 1. *Poloidal velocity image (color scale) with magnetic field lines and velocity vectors for one simulated MHD wind of our study. The dashed line depicts the sonic surface and the dotted line depicts the Alfvénic surface. Each field line is plotted with a different color.*

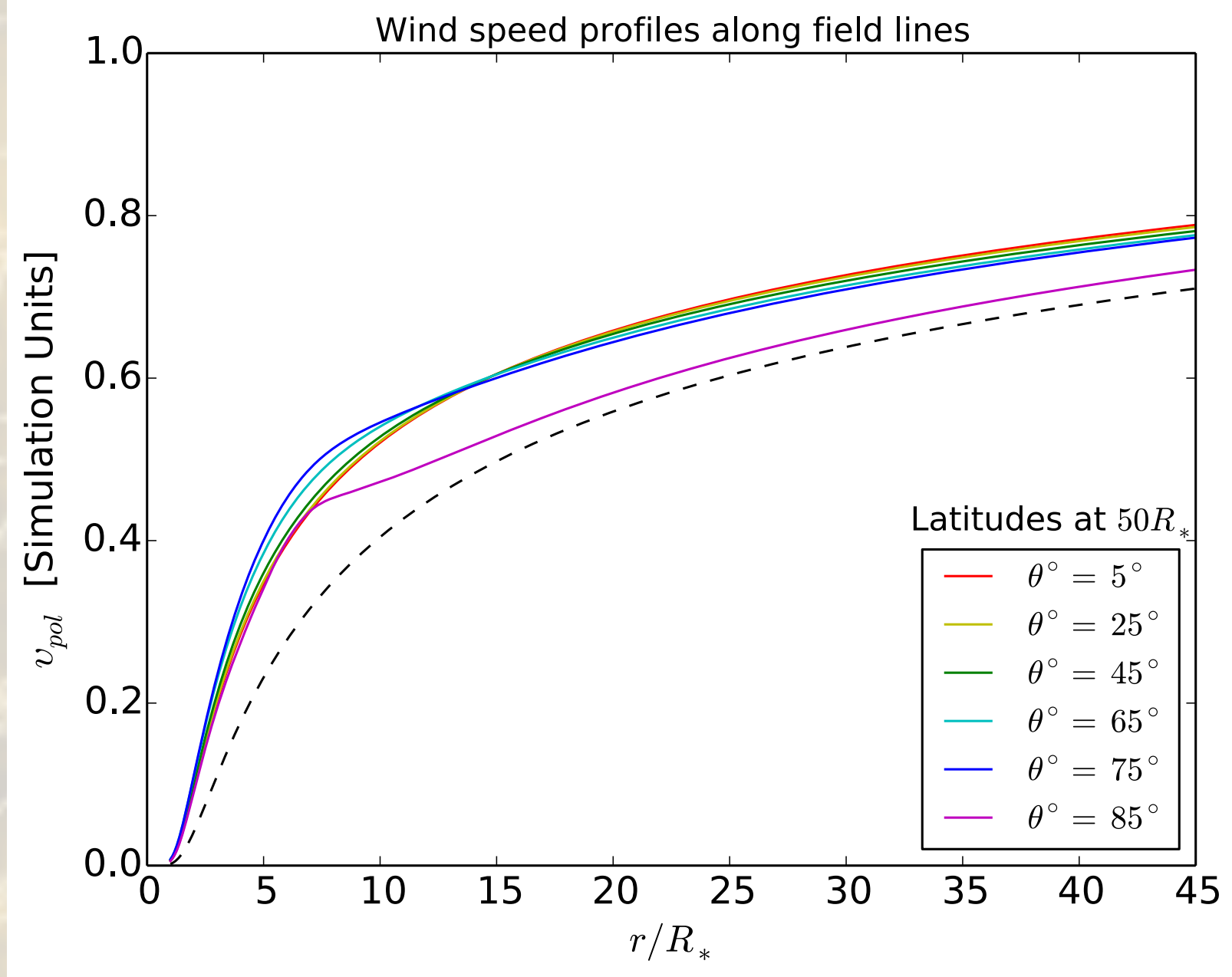
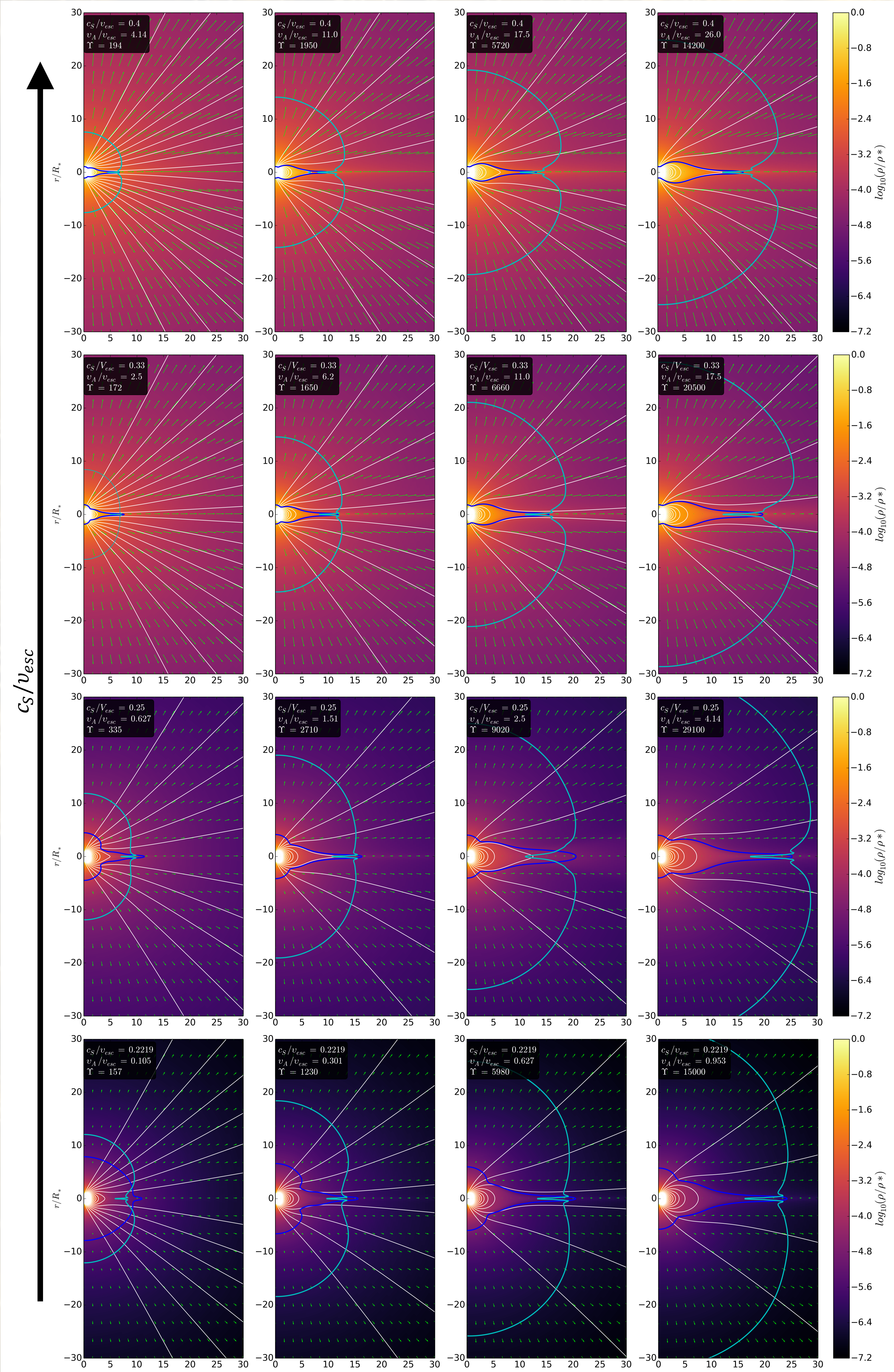


Figure 2. *Wind speed profiles along field lines at different latitudes for the case showed in fig. 1. Each line color correlates with the plotted field lines in fig. 1. For comparison the dashed line represents the velocity profile of a pure hydrodynamic wind (i.e. Parker's wind).*

c_s/v_{esc} vs Υ for Various Simulations of the Parameter Study

- Wind cases with a higher value of c_s/v_{esc} (i.e. higher coronal temperature) are faster and denser.
- The magnetization of the wind, Υ, varies along the x-axis. A higher value of Υ results in a higher value of the Alfvén radius, r_A.



$$\Upsilon \equiv \frac{B_*^2 R_*^2}{\dot{M}_w \, v_{esc}}$$

Figure 4. *Color scale of logarithmic density, magnetic field lines and velocity vectors, for various simulations of our study. The blue and the cyan lines show the location of the sonic and the Alfvénic surface respectively.*

Definitions

M_* = stellar mass.
R_* = stellar radius.
ρ_* = surface density.
P_* = thermal pressure at the stellar surface, based on the polytropic relation, $P \propto \rho^\gamma$.
B_* = surface magnetic field strength, equator.
v_{esc} = escape speed from stellar surface.
c_S = adiabatic speed of sound.
$\dot{M}_w$ = stellar wind mass outflow rate.
Ω_* = angular rotation rate of star.
f = spin rate, as a fraction of breakup speed.
τ_w = stellar wind torque.
r_A = Alfvén radius, the radius at which the speed of the flow reaches the Alfvén velocity.

Parameter Space Explored

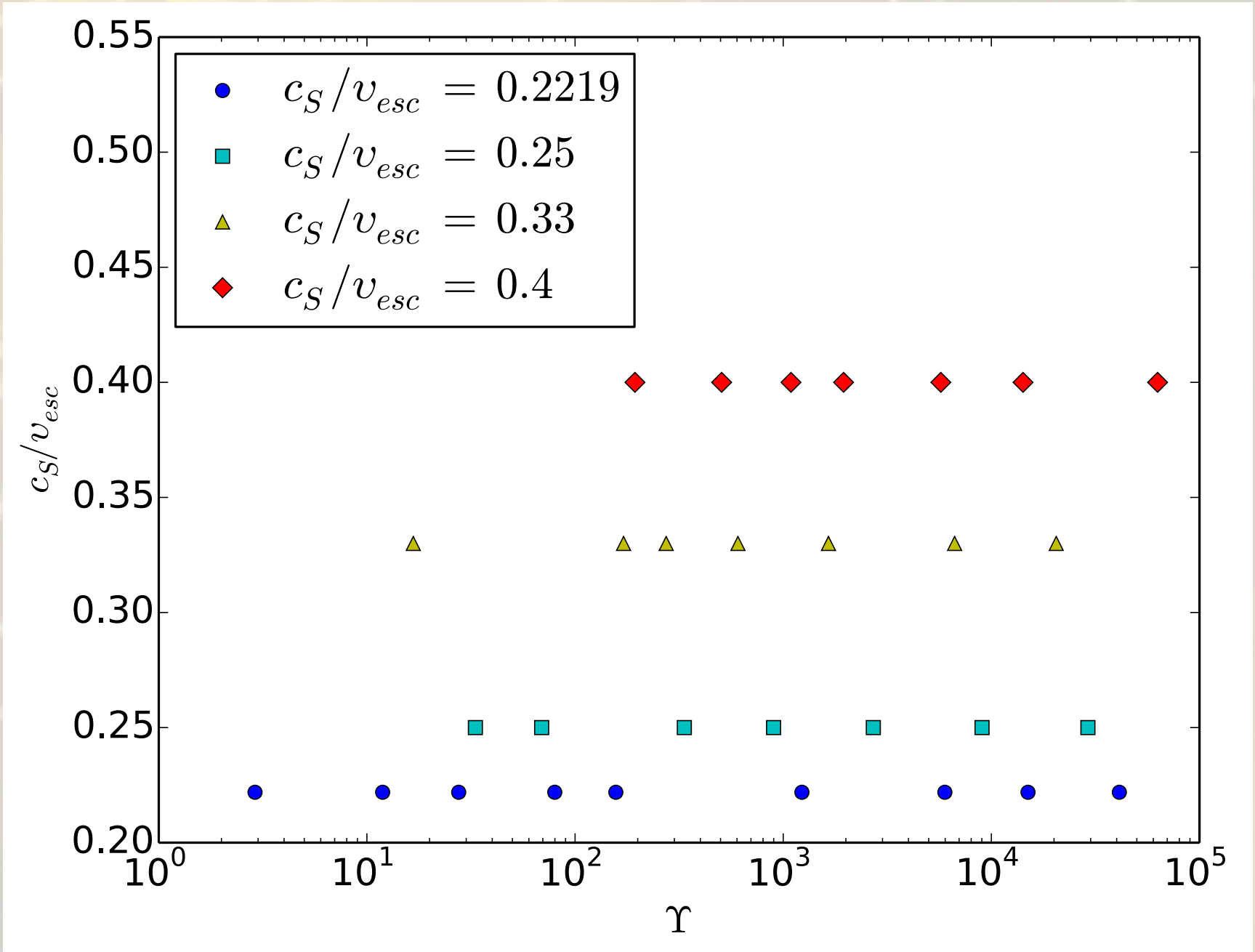


Figure 3. *The parameter space of our study. Different colors/symbols correspond to simulations with the same value of c_s/v_{esc}.*

Results: Dependence of Braking Torque on Stellar Coronal Temperature

- The torque on the star is given by

$$\tau_w = \dot{M}_w \, \Omega_* \, r_A^2,$$

where r_A is an average value. The average Alfvén radius, r_A, is the effective ***magnetic lever-arm*** that exerts a spin-down torque on the star.

- The following semi-analytic formulation is used to fit the data of the simulations in our study.

$$\frac{r_A}{R_*} = K\Upsilon^m,$$

where K and *m* are dimensionless fit constants.

☛ Dependence of r_A on Υ:

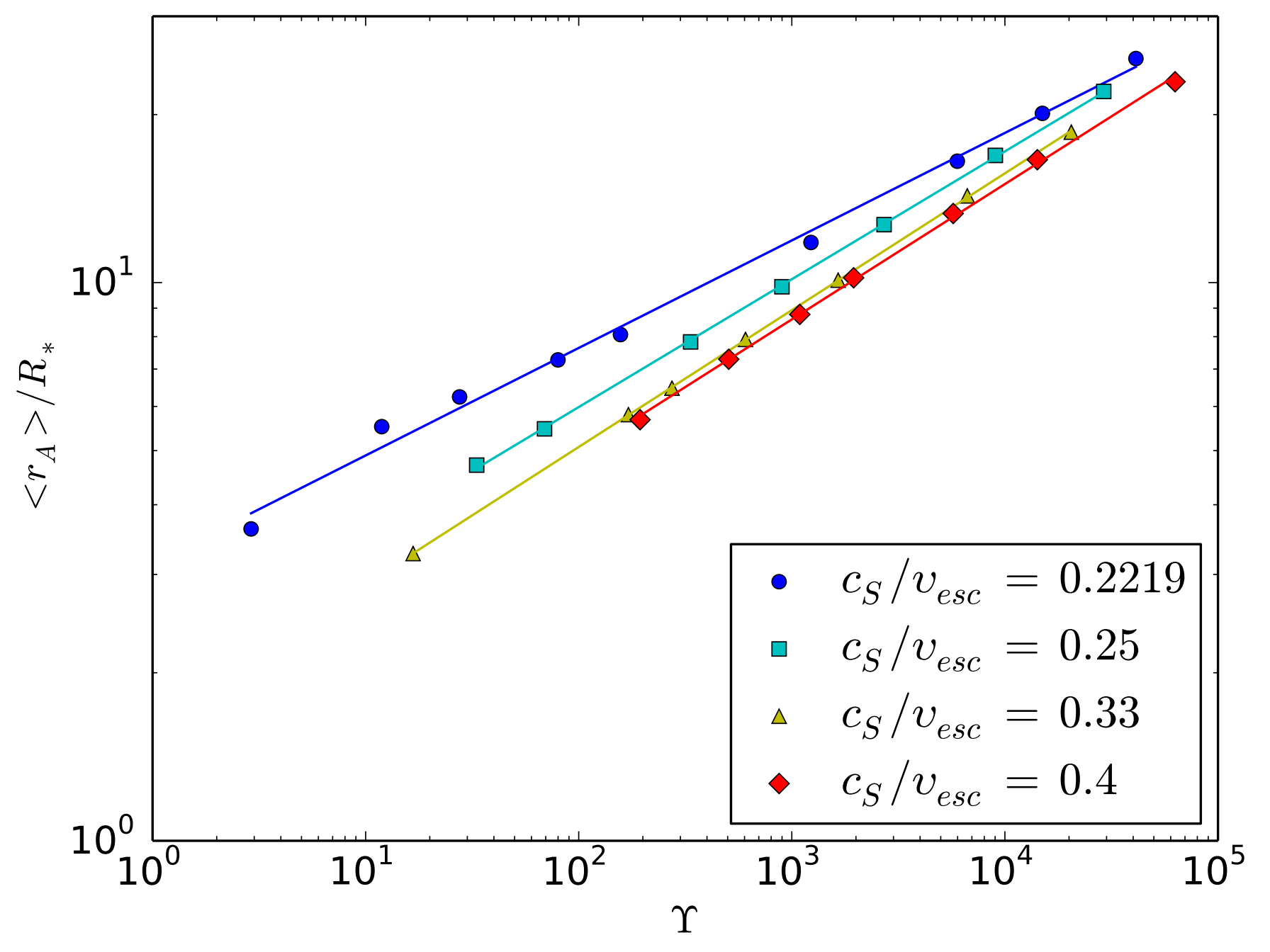


Figure 5. *The dependence of the magnetic lever-arm, r_A, on Υ for all the cases of the parameter study. Four different fits are shown and each one corresponds to a different value of c_s/v_{esc}, or in other words to a different coronal temperature.*

☛ Values of fit constants:

- ❖ $c_s/v_{esc} = 0.2219$: K = 3.15 and m = 0.193
- ❖ $c_s/v_{esc} = 0.25$: K = 2.08 and m = 0.229
- ❖ $c_s/v_{esc} = 0.33$: K = 1.64 and m = 0.246
- ❖ $c_s/v_{esc} = 0.4$: K = 1.61 and m = 0.242

☛ Formulae for Magnetic Braking:

Combining the previous two equation we obtain an expression for the torque on the star,

$$\tau_w = \frac{K^2}{\sqrt{2}} \, f \, v_{esc}^{1-2m} \, \dot{M}_w^{1-2m} \, R_*^{1+4m} \, B_*^{4m}.$$

By substituting the corresponding values of K and m for each of the coronal temperatures studied, the above relation quantifies the magnetic torque over a wide range of magnetic field strengths, assuming a fixed stellar spin rate *f*, for a dipolar magnetic field geometry.