The Effect of Combined Magnetic Geometries on Thermally Driven Winds

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Finley & Matt. (2017, Submitted)

1. Context

Sun-like stars are observed to have magnetic fields with a variety of geometries, which on large scales are dominated the lowest order fields such as the dipole and quadrupole modes. **Magnetised stellar wind outflows are primarily responsible for the loss of angular momentum** from these objects during the main sequence. Previous works have shown the reduced effectiveness of the stellar wind braking mechanism with increasingly complex, but singular, magnetic field geometries [1].

2. Project Goals

Within this poster, we quantify the impact of mixed dipolar and quadrupolar fields on the spin-down torque of Sun-like stars using 50 **MHD simulations with mixed field**, along with 10 of each pure geometries. The simulated winds include a wide range of magnetic field strength and reside in the slow-rotator regime. We produce a formula for the torque that describes all of our simulations and thus, **for the first time, predicts the stellar wind torque for mixed magnetic fields.**

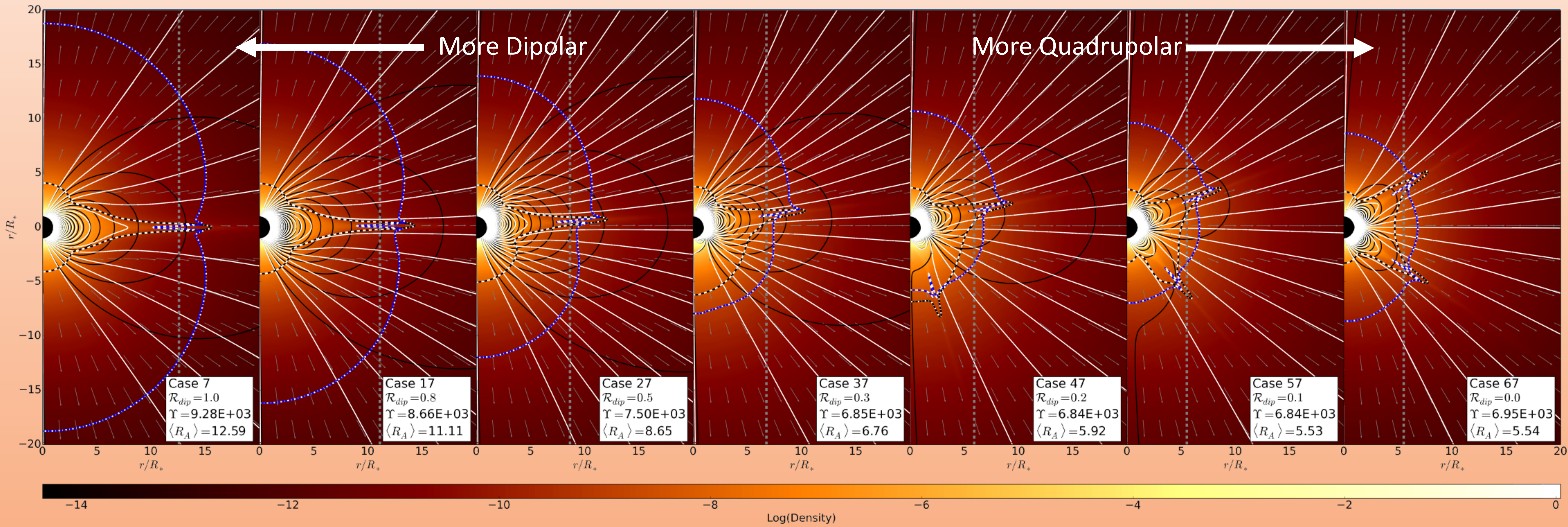

Figure 1: Logarithm of density for stellar wind simulations of dipole, quadrupole and various mixed fields. Magnetic field lines are shown with solid white lines. The Alfvén and sonic Mach surfaces are shown in blue and black respectively, in addition the fast and slow magnetosonic surfaces are indicated with dot-dash and dashed white lines. The initial field for each geometry is shown in solid black lines.

Parameters of the Simulations
The winds are initialised using the same initial polytropic parker wind solution with $\gamma = 1.05$ and $c_s/v_{esc} = 0.25$. The stellar rotation rate is set to Solar. Within the above Figure the magnetic field strength is set using the Alfvén speed over the north pole, $v_A/v_{esc} = 3.0$. The average Alfvén radius, $\langle R_A\rangle$, is shown in dashed grey vertical lines.

3. Field Addition & Morphology

We compute steady state wind solutions using the **PLUTO magnetohydrodynamics code** [2], the magnetic geometries of which are described by their polar field strength,

$$B_* = R_{dip}B_{dip} + (1 - R_{dip})B_{quad}. \quad (1)$$

Where $\boldsymbol{R_{dip}}$ **ranges from 1 to 0, for dipole to quadrupole respectively**. Examples of each R_{dip} value investigated within this work are displayed in Figure 1. For comparable values of polar magnetic field strength, the winds produce different sizes of Alfvén surface. The field geometry imprints itself onto the stellar wind, resulting in open field regions carrying the wind and dead zones with closed magnetic field loops. The global magnetic field becomes **asymmetric about the equator** for mixed dipole and quadrupole cases.

4. Semi-Analytic Torque Formulation

We parameterise our simulations using the averaged Alfvén radius, $\langle R_A\rangle$, (which acts as a torque, τ, normalised by mass loss rate, $\dot{M}$) and the wind magnetisation, Υ,

$$\frac{\langle R_A\rangle}{R_*} = \sqrt{\frac{\tau}{\dot{M}\Omega_*}} \quad (2) \qquad\qquad \Upsilon = \frac{B_*^{\,2}R_*^{\,2}}{\dot{M}v_{esc}}. \quad (3)$$

Previous torque formulations have predicted $\langle R_A\rangle$ for single geometry winds using a **power law dependence on Υ** [1], shown in Figure 2 for dipole (solid red line) and quadrupole (solid blue line),

$$\frac{\langle R_A\rangle}{R_*} = K[\Upsilon]^m. \quad (4)$$

Dipole:	$K_{dip} \approx 1.49$,	$m_{dip} \approx 0.231$
Quadrupole:	$K_{quad} \approx 1.72$,	$m_{quad} \approx 0.132$

All **70 simulations** are displayed in Figure 2, coloured by their dipole fraction. Dashed lines indicate a formulation using on the dipole fraction of the mixed field (similarly colour-coded),

$$\frac{\langle R_A\rangle}{R_*} = K_{dip}\left[\frac{B_{*,dip}^{\;2}R_*^{\,2}}{\dot{M}v_{esc}}\right]^{m_{dip}} = K_{dip}[\Upsilon_{dip}]^{m_{dip}}. \quad (5)$$

Mixed field cases fit a **broken power law**, either following a quadrupolar scaling (ep.4) for small Alfvén radii, or a scaling using only the dipole component of the field (eq. 5). **Hence, we are able to predict the spin-down torque for mixed dipole and quadrupole fields.**

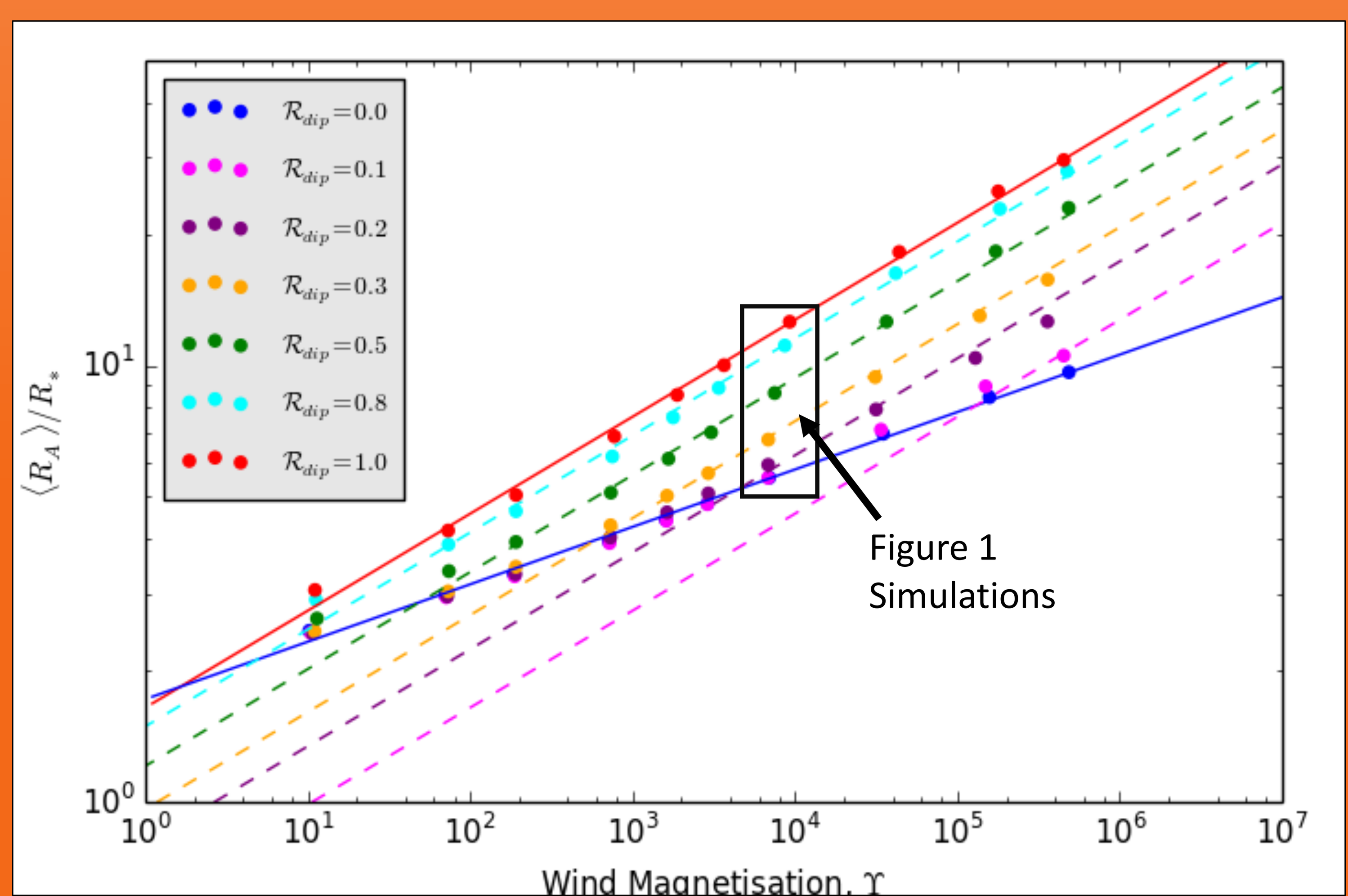

Figure 2: Average Alfvén radius vs wind magnetisation for all cases. Solid lines show the fit of dipole (red) and quadrupole (blue) to equation (4). Dashed lines show the dipolar component fit, equation (5).

References

[1] **Réville, Victor, et al.** "The Effect of Magnetic Topology on Thermally Driven Wind: Toward a General Formulation of the Braking Law." The Astrophysical Journal 798.2 (2015): 116.
[2] **Mignone, A., et al.** "PLUTO: a numerical code for computational astrophysics." The Astrophysical Journal Supplement Series 170.1 (2007): 228.