What Causes the Rotation Period Gap in Young Clusters?

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Abstract

We model the rotation rates of low-mass stars (0.1 - 1.3 $M_\odot$), to explain the broad distributions observed at ages of ~0.1 - 1 Gyr.

Our model:

- Uses a **new wind torque** formulation.
- **Fits observations** better than earlier models.
- Suggests that **core-envelope decoupling might not be needed** to explain observations.
- Predicts that magnetic field and/or wind mass loss rates are suppressed in fast rotators.

What *is* the "Period Gap"?

Young clusters show a broad distribution of rotation periods. The "gap" is the region between the fastest and slowest rotators, *sometimes* showing a dearth of stars.

Goal: To explain the observed distributions.

"*Despite the name, the region is not empty.*"

– Barnes '03

New Stellar Wind Torque

We present a new formulation, motivated by physics, and empirically tuned.

From MHD simulations (Matt+ '12):

$$T = T_\odot \left(\frac{R_*}{R_\odot}\right)^{3.1}\left(\frac{M_*}{M_\odot}\right)^{-0.22}\left(\frac{\Omega_*}{\Omega_\odot}\right)\beta^{-0.44}\left(\frac{B_*}{B_\odot}\right)^{0.88}\left(\frac{\dot{M}_w}{\dot{M}_{w,\odot}}\right)^{0.56}$$

"Magnetic activity" factor

Symbols: $T_\odot$ = torque for the Sun; stellar radius, mass, angular rotation rate, surface dipole field strength, and mass loss rate. The factor β is due to centrifugal effects (order unity).

Tuned to fit observed spin rates:

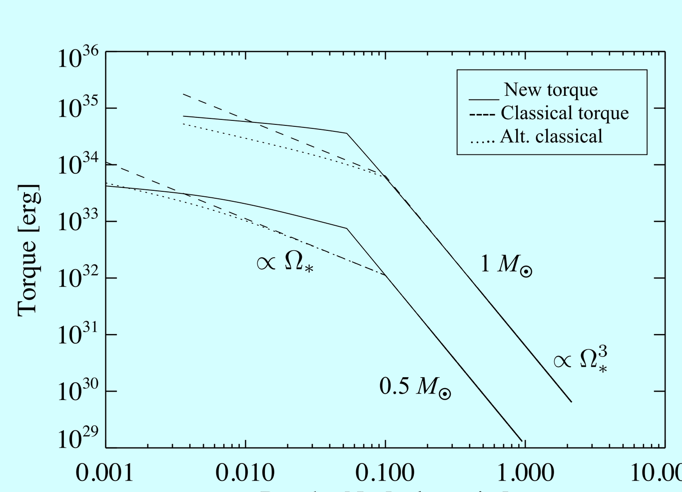
$$\left(\frac{B_*}{B_\odot}\right)^{0.88}\left(\frac{\dot{M}_w}{\dot{M}_{w,\odot}}\right)^{0.56} = \left(\frac{M_*}{M_\odot}\right)^{0.72} \mathrm{Min}\left[1000\left(\frac{Ro}{Ro_\odot}\right)^{0.35}, \left(\frac{Ro}{Ro_\odot}\right)^{-2}\right]$$

New, to reproduce the gap

To give Skumanich spin-down

Ro = Rossby number = rotation period / convective turnover timescale.

Normalization: $T_\odot = -6.3 \times 10^{30}$ erg



***New stellar wind torque (solid line)** for 2 different masses vs. Ro.*

***Dashed line ("classical torque")** was used by Matt+ '15 and similar to, e.g., Macgregor & Brenner '91, Krishnamurthi+ '97, Bouvier+ '97, Barnes '10, Denissenkov '10, Irwin+ '11, Spada+ '11, van Saders & Pinsonneault '13, Somers+ '17.*

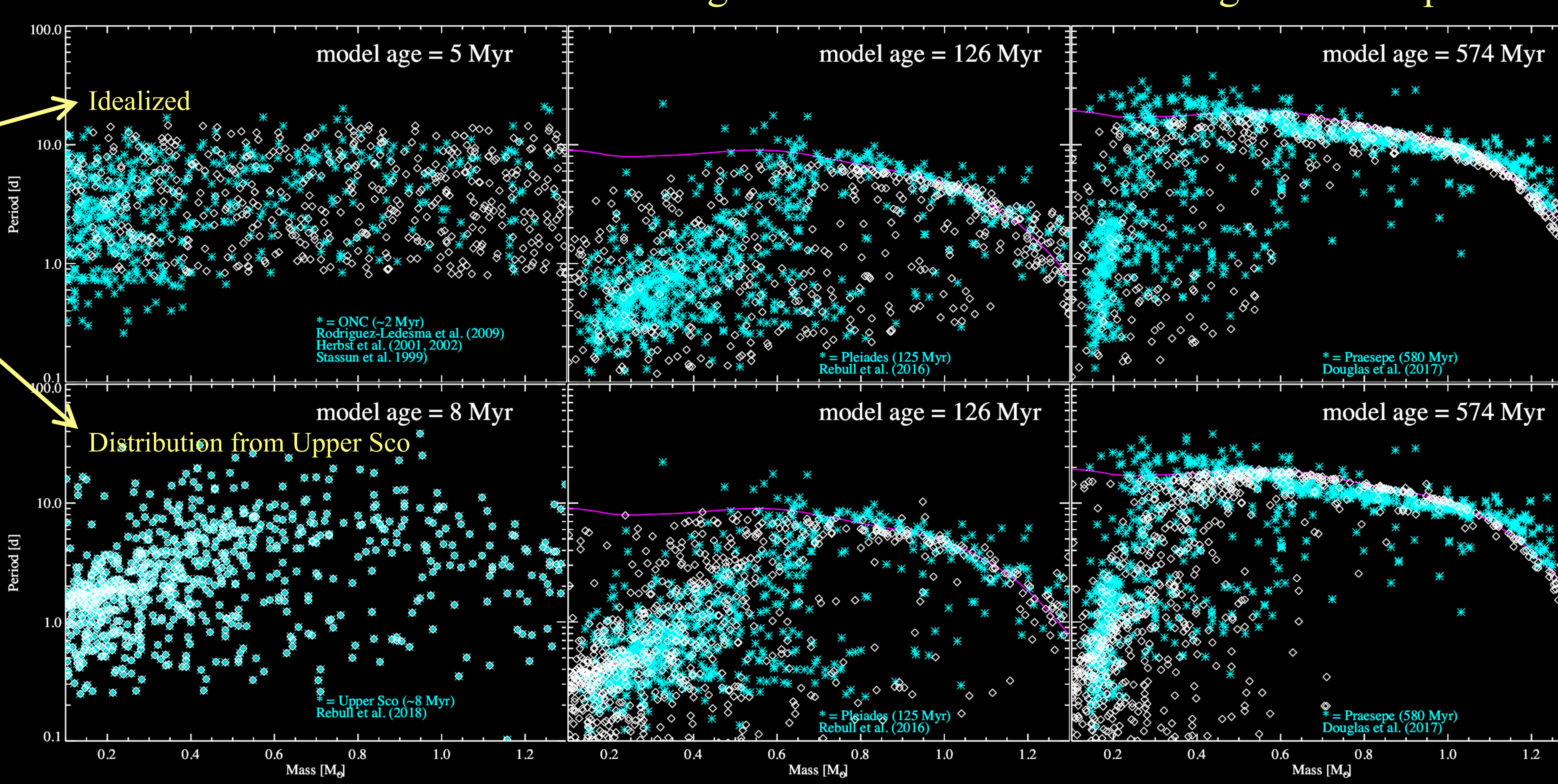
***Dotted line** is similar to Johnstone+ '15, Amard+ '16, Ardestani+ '17.*

Modeled Stellar Rotation Rates vs. Observations

Spin-Evolution Models:

Assume:

- Initial conditions
- Solid-body rotation
- **New wind torque**
- Stellar structural evolution from Baraffe+ '98

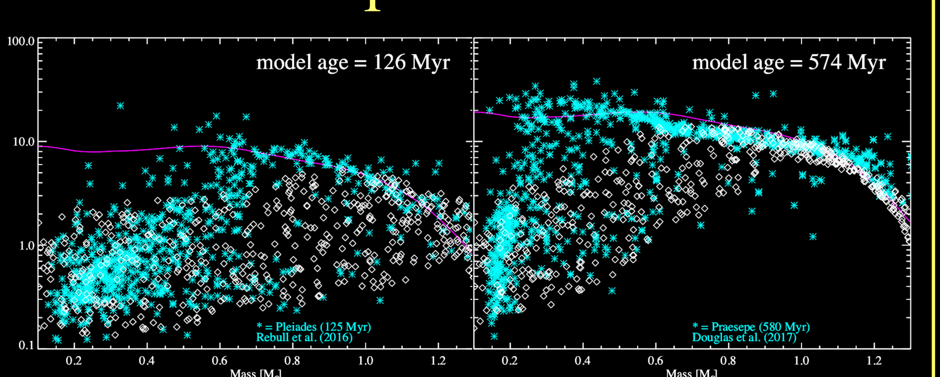


***Evolution of a modeled stars** (white diamonds), **compared to observed rotation rates** (cyan stars). We evolve 2 different initial distributions (left panels) to the age of the Pleiades (middle panels) and Praesepe (right panels) open clusters.*

***Top**: Initial condition (5 Myr) is idealized and similar to the ONC. **Bottom**: Initial condition (8 Myr) is taken from the observed distribution of Upper Sco. Some structure persists for ~600 Myr.*

Classical Torque Doesn't Make a Gap

Assuming solid-body rotation, it can't explain low-mass, slow rotators.



*Modeled stars (white diamonds), compared to observed rotation rates (cyan stars), **evolved using the classical torque** (dashed line in bottom left of poster).*

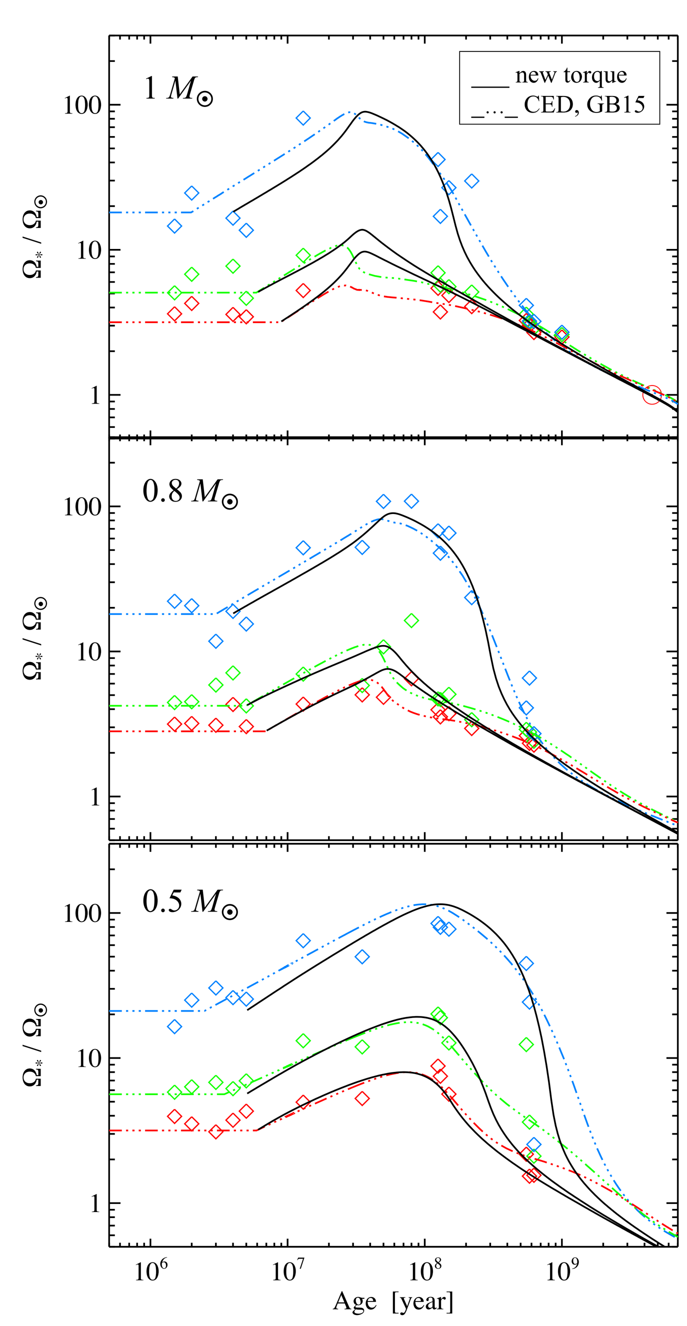
Conclusions:

- New torque produces distributions similar to observations.
- Structure in "initial conditions" explains some of the substructure in older clusters.

Comparison With Previous Models

Core-Envelope Decoupling (CED)?

- Allows core to rotate much faster than envelope.
- Modifies the surface rotational evolution.



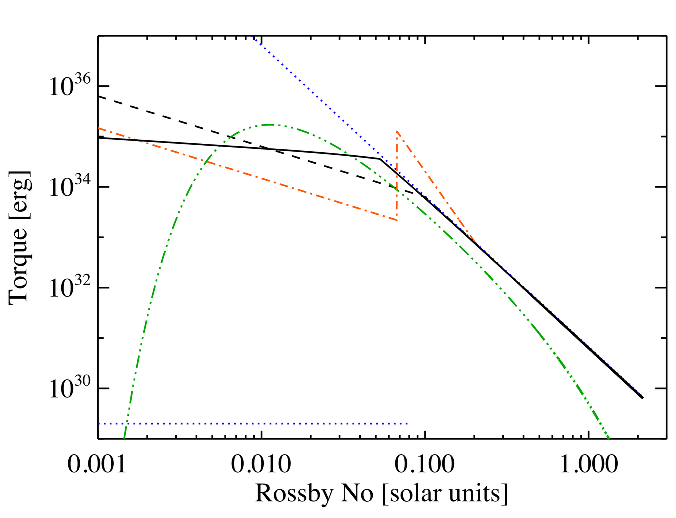
***Rotation tracks for 3 initial spin rates** and 3 different masses.*

***Solid lines** use the new torque and solid-body rotation.*

***Dash-3-dot lines** show tracks from Gallet & Bouvier '15 (GB15), which includes CED.*

***Diamonds:** 25th (red), 50th (green), & 90th (blue) percentile of **observed rotation rate distributions** of several clusters (from GB15).*

Other Proposed Torques?



***Classical torque** (Dashed).*

*"**Metastable Dynamo," Brown '14** (dotted), proposes strong dynamo "switches on" at random time in young stars.*

*"**Catastrophic Braking," Gondoin '17** (dash-dot), proposes sudden increase in mass loss rate.*

*"**The Revolution Revolution," Garraffo+ '18** (dash-3-dot), proposes small-scale magnetic field dominates for fast rotators.*

***New torque** (solid), proposes relatively subtle flattening of T vs. Ro.*

Conclusions:

Our new torque (+ solid-body rotation):

- Is simpler and fits data better than others proposed.
- Fits data as well as CED models in 3 mass bins, but...
- Also fits fully convective M dwarfs, where CED can't operate.

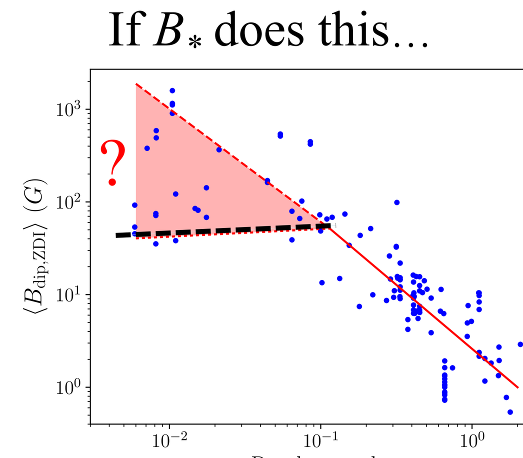
Implications for Mass Loss Rates and Magnetism

The new torque specifies the "magnetic activity" factor:

$$B_*^{0.88}\dot{M}_w^{0.56}$$

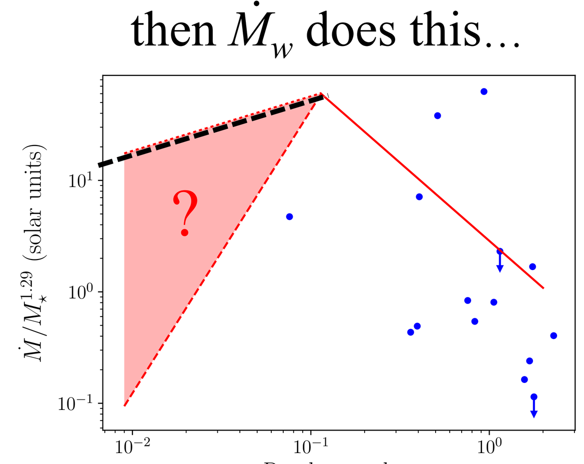
If correct, B_* and $\dot{M}_w$ must vary accordingly.

If B_* does this...



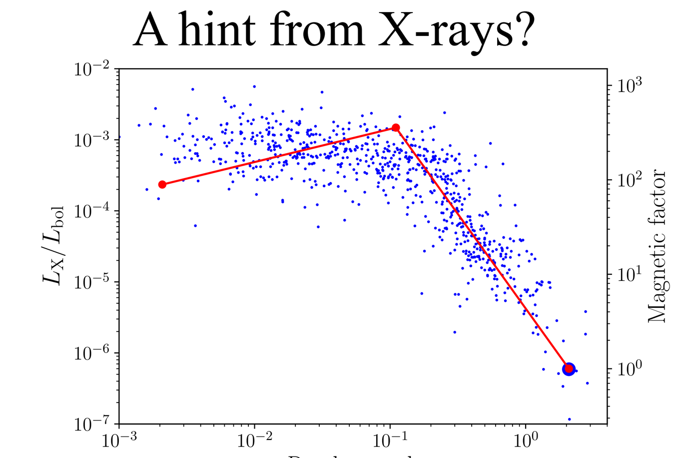
***Dipole field strength measured with ZDI** (blue points; compiled by See+ in prep.) vs. Ro. The lines show **range of possible scalings of B_* with Ro**.*

then $\dot{M}_w$ does this...



***Mass loss rates** ($\div M_*^{1.29}$) measured by Wood+ '14 (blue points) do not show obvious trend with Ro. Lines show required variation, corresponding to the lines in plot of $\langle B_{dip,ZDI} \rangle$.*

A hint from X-rays?



***X-ray luminosity** (L_X/L_{bol}; blue points; left scale; from Wright+ '11). The red line (right scale) shows the **magnetic activity factor**. X-rays don't show the same trend in the saturated regime.*