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On the Relationship Between Stellar Rotation and Radius in Young Clusters

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Abstract. We examine the early angular momentum history of stars in young clusters. We reported (Rebull et al., in preparation), based on 197 photometric periods in the Orion Flanking Fields and 83 photometric periods in NGC 2264, that PMS stars apparently do not conserve stellar angular momentum (J) as they evolve down their convective tracks, but instead evolve at nearly constant angular velocity (ω). This result is inconsistent with expectations that convective stars lacking disks should spin up as they contract, but consistent with disk-locking models.

We have now mined the literature for data on 12 additional clusters ranging in age from Orion to the Hyades, finding data for 1141 K & M stars such that we can plot stellar rotational velocity vs. radius. *Taken together, these data reinforce our initial conclusion that PMS stars spanning ages ~0.1–~10 Myr do not appear to spin up in response to contraction, and further suggest that any spin up between 10 Myr and the ZAMS is modest (< 2×) at best.*

1. Introduction

- When PMS stars first appear, they rotate well below breakup velocity (most 10s km/s, breakup ~300 km/s).
- This is a surprise, since many are still accreting and are in principle gaining angular momentum (J) from their disks.
- These data have motivated models (e.g. Königl 1991, Shu et al. 2000) which posit star-accretion disk interactions that lock PMS objects to near constant angular velocity (ω).
- When the accretion phase ceases, these models predict that stars should spin up in response to contraction, conserving stellar J.
- Rotation periods (P) and/or projected rotational velocities ($v \sin i$) are now available for a large number of PMS stars and enable tests of both these predictions.

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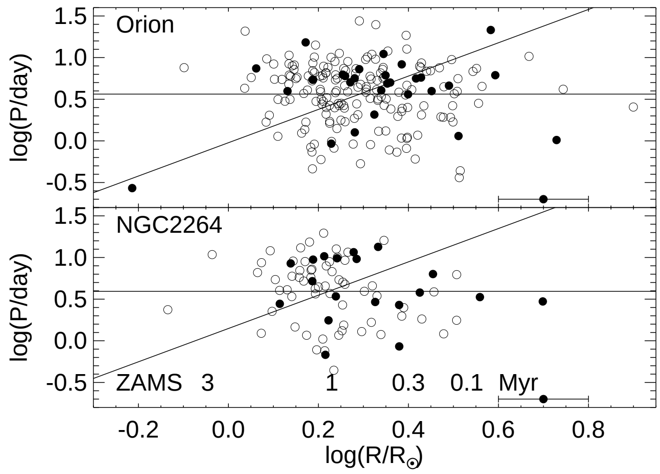

Figure 1. P vs. R for stars in the Orion Flanking Fields and NGC 2264, without $I-K$ excesses (open symbols) and with excesses (filled symbols). Typical error bars are indicated, as are approximate ages for the mean mass found in these clusters and D'Antona & Mazzitelli (1994) models. Lines correspond to constant P (J decreases with age) and constant J (P decreases with age). These data are complete between 0.3 and 25 days. Stellar J apparently decreases with age!

- Rebull et al. (2001) show that while PMS stars in Orion and NGC 2264 with and without circumstellar disks show similar rotation properties, *there is no evidence of the expected spinup in rotational velocity as stars approach the ZAMS* (see Figures 1 and 2).

2. Observations & Analysis

- This poster extends our analysis by mining the literature for rotational data (P or $v \sin i$), V, I, and spectral types for 1141 K & M stars in Orion, Chamaeleon, Taurus-Auriga, ρ Oph, NGC 2264, TW Hya, Lupus, η Cha, IC 2391, IC 2602, α Per, Pleiades, and Hyades. (As a result of limited space in the present volume, a full list of the more than 70 papers consulted for these data will be found in our journal article in preparation, Rebull et al. 2001b.)
- For all stars, radii (R) were calculated from their positions in the dereddened CMD.
- The rotational velocities v were then derived from R and P via $2\pi R/P$.
- If stellar $J \propto \frac{Rv}{M}$ is conserved, then $P \propto R^2$, or $v \propto 1/R$.
- Figures 2 and 3 instead suggest that v is essentially constant at least to ages $\sim$10 Myr, and possibly to the ZAMS.

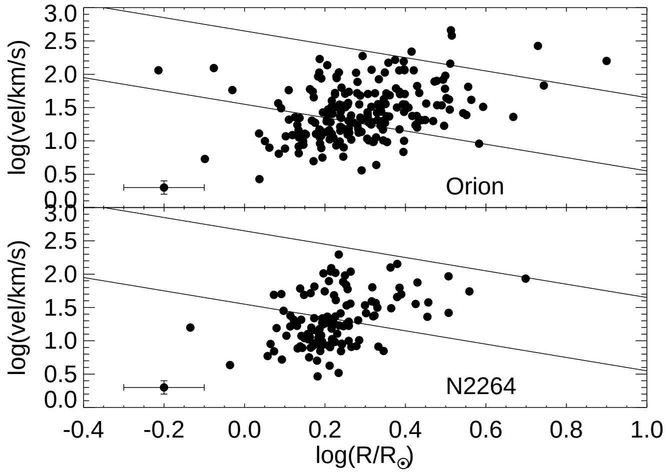

Figure 2. The same complete data set from Figure 1, converted to v vs. R. Typical error bars are indicated. The parallel lines show the change in velocity expected if J is constant and independent of R (and hence independent of age). The placement and separation of the two lines was chosen to encompass the observed range in velocities for the youngest (largest R) PMS stars. If J were constant, then the stars would be expected to remain between the two parallel lines as they evolve. Clearly they do not!

- *This means that stars LOSE angular momentum throughout their approach to the ZAMS!*
- We obtain $d \log J / d \log t \sim -0.4$ over $\sim$3-10 Myr, or $d \log J / d \log R \sim 1.9$ over $\sim$1-4 $R_\odot$.

3. Three Possible Explanations

Dust-Free Gaseous Disks

- We expect to find constant angular velocity with time if disk locking works to ages $\sim$10 Myr.
- But, the large majority of these stars lack the near-IR excesses typically used to diagnose disks.
- Hence, if disks play a role, they must be gaseous, free of the micron-size dust grains that produce IR excesses.
- SIRTF can search for the molecular hydrogen emission diagnostic of such gaseous disks.

J Loss via Stellar Winds

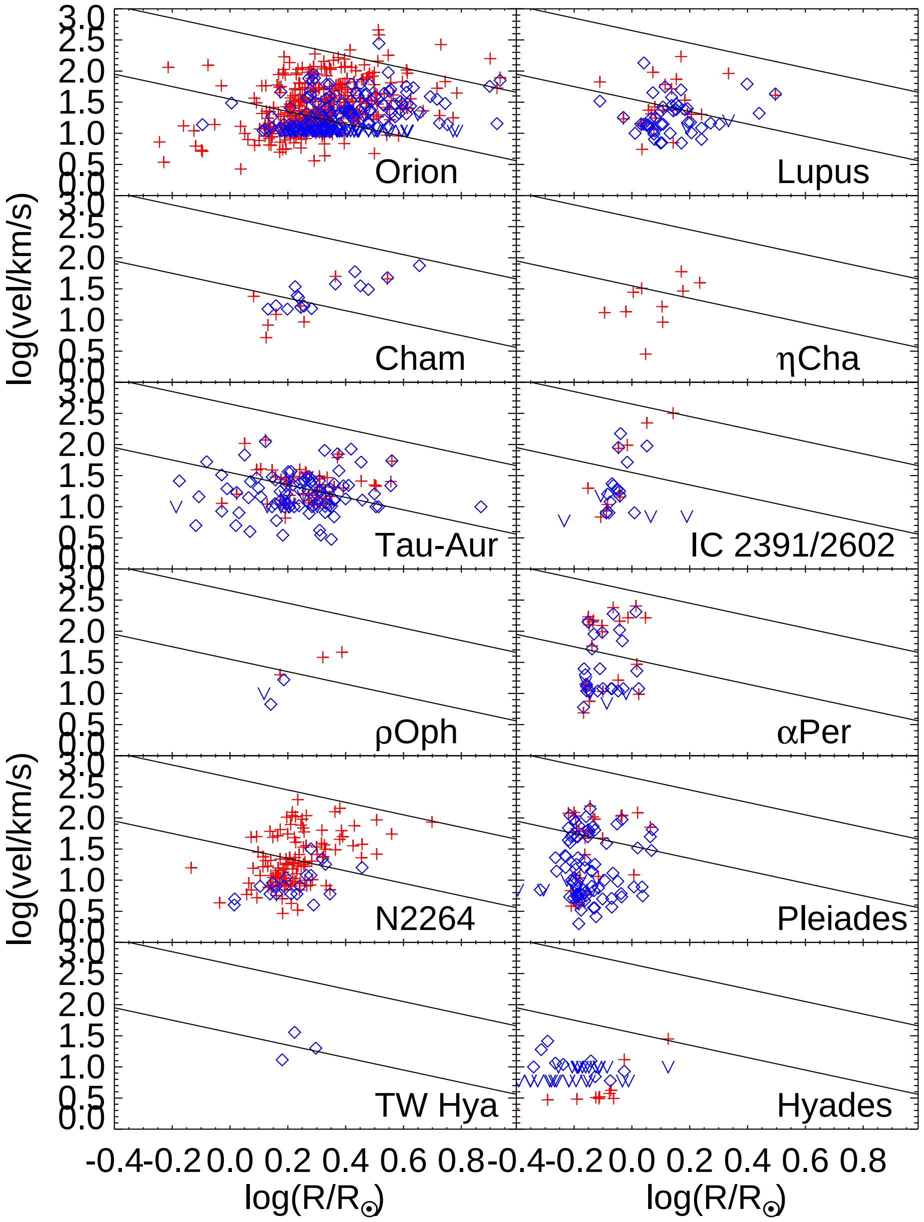

Figure 3. Rotational data from clusters in the literature. Red crosses are v calculated from P; blue diamonds are measured $v \sin i$ (or upper limits as appropriate). Parallel lines are identical to those in Figure 2, and represent expected slope if J is conserved ($v \sim 1/R$). Instead, $v \sim$ const, or $J \sim R$ to log $R/R_\odot \sim 0.1$ or within a factor of two of their final ZAMS radii.

- Stellar winds loaded onto open magnetic field lines can exert a spindown torque on stars.
- According to standard models, these stars are both young enough and low-mass enough to be fully convective and therefore are thought to rotate like solid bodies.
- Therefore, any wind model must *slow down the entire star*, not just its outer layers, and account for $d \log J/d \log t \sim -0.4$ over ~3-10 Myr.
- Uncer current assumptions (e. g. MacGregor and Charbonneau 1994), the spindown $t>$evolutionary t by a few orders of magnitude.
- Maybe the outer layers are really decoupled from the interior, so we only have to brake the outer layers, not the whole star. However, such a decoupling not expected.

J Loss via Tidally-Locked Planetary Companions

- Tidal locking between a close-in Jupiter and star can transfer stellar spin J to planetary orbital J.
- However, this fails by 2 orders of magnitude, because (1) the planet must be close enough to produce significant tides; and (2) the planet must be far enough from the star to dominate the system J.

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Table 1. Cluster ages & distances

cluster	(DAM) age range from data (Myr)	age in lit. (Myr)	distance (pc)	mean $\log(R/R_{\odot})^{a}$
Orion	0.1−10	1−3	470±70	0.33±0.07
Cham	0.3−3	2−20	160±20	0.30±0.06
Tau-Aur	1−30	1−10	150±10	0.27±0.03
ρ Oph	∼1	<3	130±15	0.24±0.05
NGC 2264	0.3−10	3−5	760±30	0.23±0.03
TW Hya	∼1	10	50±30	0.23±0.03
Lupus	0.3−10	1−3	150±30	0.13±0.08
η Cha	3	7	97±4	0.076±0.02
IC 2391 & 2602	1−10	30-50	155±5	−0.044±0.01
α Per	>10	50-90	175±10	−0.12±0.03
Pleiades	>30	115	132±15	−0.15±0.06
Hyades	>30	630	47±2	−0.20±0.02

[a]Error quoted in mean log R is systematic error resulting from uncertainty in distance, representing a uniform shift of the points in Figure 3. Astrophysical and instrumental error has been estimated to be $\delta\log R \sim 0.1$.