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The Evolution of Angular Momentum of Intermediate Mass Stars: From the Birthline to the Main Sequence

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Abstract. Measurements of stars in the Orion OB association show that there is a continuous power law relationship between specific angular momentum (J/M) and mass (M) for stars on *convective* tracks having masses in the range ~0.5 to ~3 $\mathrm{M}_\odot$; this power law extends smoothly into the domain of more massive stars on the ZAMS. If we assume that stars are "locked" to circumstellar accretion disks via their magnetic fields until they are deposited on the stellar birthline, we can account for the observed slope and zero point of the power law fit to the upper envelope of the observed J/M vs M distribution.

Pre-main sequence stars with $M<2$ $\mathrm{M}_\odot$ on *radiative* tracks do not follow the power law relationship. A sharp decrease in J/M with decreasing mass has been recognized for more than 30 years for older field stars, but remarkably is seen already among our Orion sample of stars that are only a few million years old. We show that this break in the power law is a consequence of loss of angular momentum on convective tracks, combined with core-envelope decoupling at the time of the transition from the convective to radiative tracks.

1. Introduction

Substantial progress has been made over the past several years (e.g. Herbst, Bailer-Jones, & Mundt 2001; Rebull 2001 and references therein) in characterizing the early evolution of angular momentum of low mass ($M<0.5$ $\mathrm{M}_\odot$) pre-main-sequence (PMS) stars. In this paper, we explore the evolution of angular momentum in PMS stars with masses in the range 0.5–3 $\mathrm{M}_\odot$. The goal is to establish the initial values of angular momentum (J) and to infer the primary factors that affect rotation as a function of time and mass.

As a framework for this exploration, we will assume that protostars are locked to their surrounding accretion disks via magnetic fields until they arrive at the birthline (Stahler 1983) and that the disk applies a braking torque (Königl 1991; Shu et al. 1994). We will show that subsequent changes in angular momentum and surface rotation as PMS stars evolve onto the main sequence result from: 1) continued loss of angular momentum via coupling to disks at the lower accretion rates characteristic of T Tauri stars; 2) changes in the moment of inertia as a result of changes in stellar radius and internal structure; and 3) decoupling between rotation of the core of the star and its envelope.

2. Initial Values of Specific Angular Momentum

The Orion OB Association provides an ideal sample for establishing initial angular momentum because it (1) contains a statistically significant number of PMS stars having $M > 0.5\ M_\odot$; and (2) includes objects born in multiple star-forming episodes so that stars of identical mass can be observed in a variety of evolutionary states.

The specific angular momentum of a star is given by the relationship

$$J/M = I\omega/M$$

where J is the total angular momentum, M is the mass of the star, I is the moment of inertia (taken from models of PMS stars by Swenson et al. 1994) and ω is the angular velocity. Since we measure $v \sin i$, we can only calculate $J \sin i$.

Figure 1 shows the plot of $J \sin i/M$ as a function of mass for stars that are still on their convective tracks and for stars with $\log T_{\rm eff} > 4.0$, which are already on the ZAMS. To extend the upper bound of the data to lower masses, we have also plotted $<J/M>$ multiplied by $<\sin i> = \pi/4$ for the upper quartile of the much larger sample of stars for which Rebull (2001) has obtained periods. The figure shows that there is power law relationship between J/M and M for stars on convective tracks throughout the mass range 0.1–3 $M_\odot$ and that this power law merges smoothly with the data for higher mass stars on the main sequence.

The continuity of the upper bound for J/M in Fig. 1 suggests that the origin of stellar angular momenta is similar for stars throughout this large range in masses. Let us hypothesize that accreting stars are locked to their disks as proposed by Königl (1991) until they reach their birthlines. The angular velocity of a star locked to its disk is given by

$$\varpi = \varepsilon(GM/R_{\rm in}^3)^{1/2}$$

where $\varepsilon<1$ is the ratio between the stellar angular velocity and the Keplerian velocity at $R_{\rm in}$, i.e., at the radius where the disk is disrupted. This radius in turn is given by

$$R_{\rm in} = \beta\mu^{4/7}(2GM)^{-1/7}\dot{M}^{-2/7}$$

where β is a parameter ≤ 1 (with $\beta = 1$ corresponding to the classical Alfvén radius for spherical accretion), μ is the stellar dipole moment, and $\dot{M}$ is the mass accretion rate. Using these equations plus the relationship that the surface magnetic field $B = \mu/R^3$, we then find that

$$J/M = I\varpi/M = [I\varepsilon(GM)^{5/7}(2)^{3/14}\dot{M}^{3/7}]/(M\beta^{3/2}B^{6/7}R^{18/7}).$$

To evaluate this expression, we will set set $\varepsilon = \beta = 1$; adopt $B = 2500$, which is typical of the limited measurements to date for T Tauri stars (e.g. Guenther et al. 1999; Johns-Krull, Valenti & Koresko 1999); and assume accretion rates of either 10^{-5} $M_\odot {\rm yr}^{-1}$ (Palla and Stahler 1992) or $10^{-5}(1, M^{1.5})$ $M_\odot {\rm yr}^{-1}$, whichever is larger (Behrend and Maeder 2001).

The models of PMS stars do not extend beyond 5 $M_\odot$, and so we have terminated our calculations at this point. As Fig. 1 shows, the very simple assumptions made here yield both a zero point and a slope that are remarkably

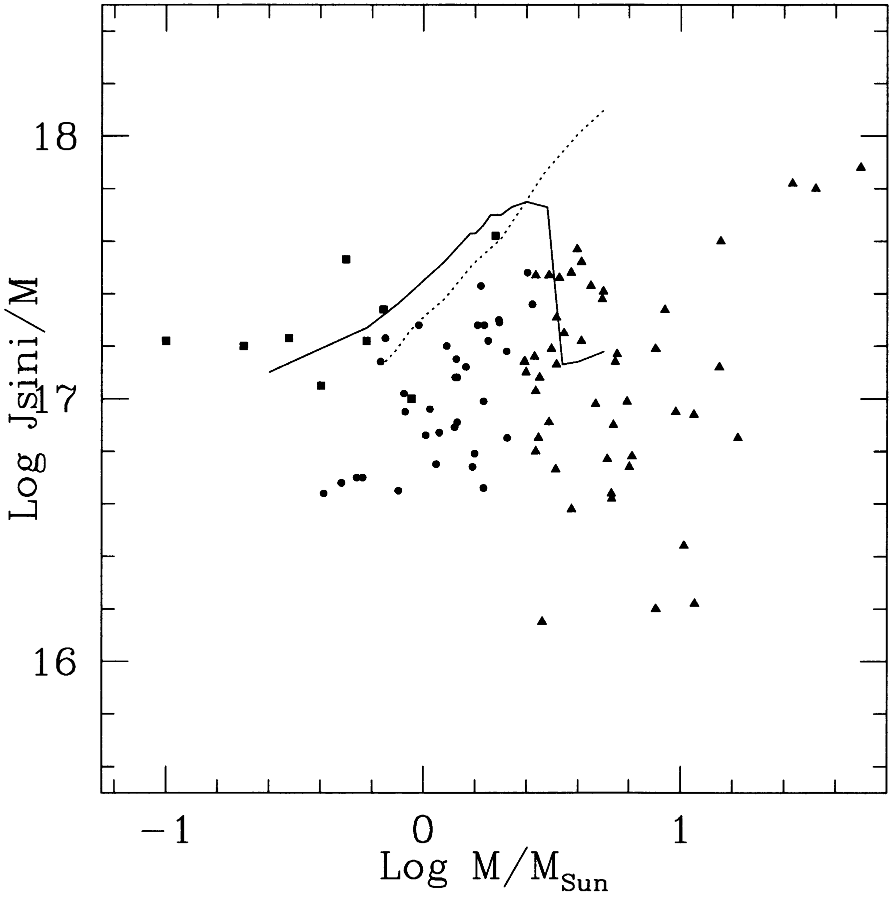

Figure 1. Initial angular momentum. Initial values of specific angular momentum ($J \sin i/M$). Filled circles represent Orion stars in the current sample that are on convective tracks; filled squares are the average of the upper quartile of stars in Rebull's (2001) study of the Orion flanking fields; triangles are stars with $T_{\rm eff}$>10,000 K, which are already on the main sequence. The curves show the predicted values of J/M along the Palla-Stahler birthline (solid line) and the Behrend-Maeder birthline (dashed line) on the assumption that the rotation of protostars is locked to a disk until the stars are released on the birthline. The break in the PS birthline marks the transition between the case where the birthline intercepts convective tracks (low mass stars) and where it intercepts radiative tracks.

close to what is observed. The broad scattering of stars below the upper bound might be caused by variations in $\sin i$, magnetic field strength, accretion rates, or by the fact that those stars that remain locked to their disks while they evolve down their convective tracks are accreting mass currently at a much lower rate than prior to the time they were deposited on the birthline and they are locked to a lower rotation rate.

Similar results are found from the theory introduced by Shu et al. (1994), despite the fact that in the former case the disk acts as the primary source of angular momentum loss, while in the latter, angular momentum is lost via a wind driven off the disk at the disk-stellar magnetosphere boundary.

3. From the Birthline to the Main Sequence

Figure 2 shows the relationship between J/M and M for Orion stars on PMS *radiative* tracks. The data for stars with $\log T_{\rm eff} > 4.0$ are repeated from Fig. 1. It has been known for more than 30 years that there is a sharp break in the power law at about 2 $M_\odot$ for main sequence stars. Here we see that the break is present already in Orion stars on radiative tracks that are only a few million years old.

In order to account for the observed changes in angular momentum as stars evolve from the birthline to the main sequence, we need to take two processes into account: 1) additional loss of angular momentum as stars evolve down their convective tracks; and 2) core-envelope decoupling during the transition from convective to radiative evolution.

Loss of angular momentum along convective PMS tracks is the primary cause of the observed break in the power law at 2 $M_\odot$. During this phase of evolution, coupling between the stellar magnetosphere and the circumstellar disk will cause the star to spindown. Three factors determine the amount of spindown: 1) the time spent on the convective track; 2) the time scale for disk-braking; and 3) the lifetime of the disk. Theoretical calculations of spindown (Hartmann 2002) predict that low mass stars spend enough time evolving down convective tracks to lose a significant amount of angular momentum while stars with masses close to 2 $M_\odot$ do not. Observations (Rebull et al. 2002 and this symposium) indicate that solar-mass stars lose about a factor of 10 in angular momentum as they evolve down their convective tracks, which is very nearly what is required to account for the break in the power law.

We can also show that core-envelope decoupling during the transition from convective to radiative tracks is required to account for the final values of rotation on the main sequence. If angular momentum cannot be efficiently transported across adjacent spherical shells or from the radiative core to the convective envelope, then at any given time t the rotational velocity v is given by

$$v(t) = v_0 \times R_0/R(t)$$

where R is the radius of the star and v_0 and R_0 refer to initial values.

If angular momentum is transported efficiently throughout the star, and the star rotates as a solid body, then

$$v(t) = v_0 \times (I_0/R_0) \times R(t)/I(t).$$

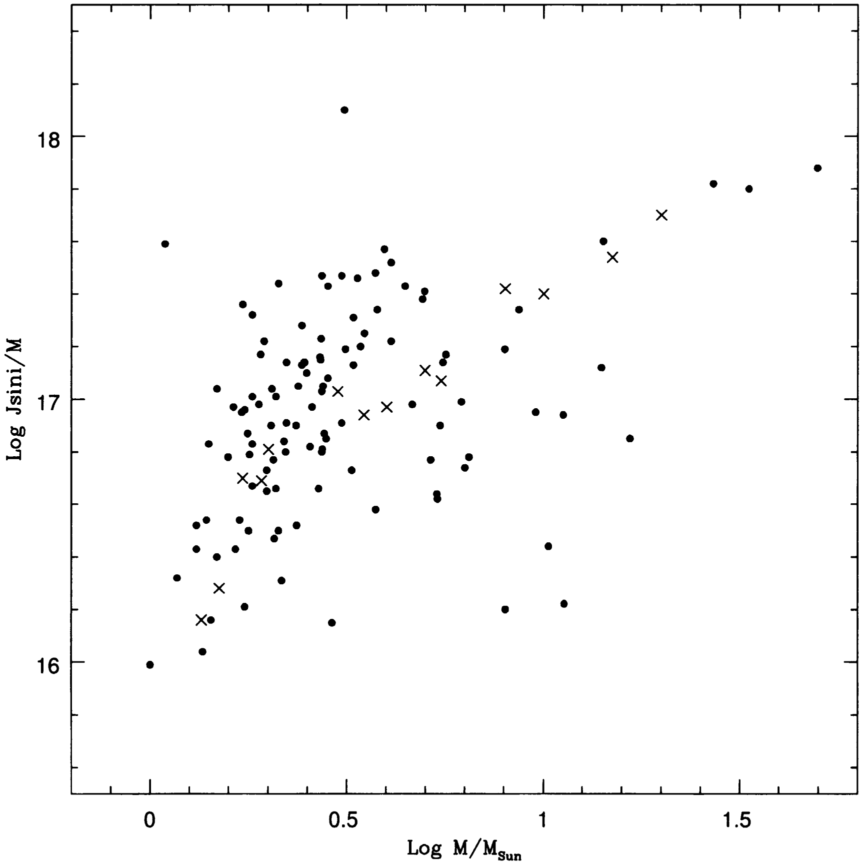

Figure 2. The values of specific angular momentum ($J \sin i/M$) for PMS stars on radiative tracks (M<3 M$_\odot$) or on the main sequence are shown by filled circles. Crosses show $<v \sin i>$ for main sequence field stars.

We test these two extreme cases against the data by predicting the rotation rates that convective stars in our sample will have when they reach the ZAMS. The average mass of the stars on convective tracks in our sample is 1.74 $M_\odot$, and so we have used main sequence stars in the mass range 1.5–2 $M_\odot$ (Wolff & Simon 1997) as a comparison sample. Figure 3 shows that the assumption of solid body rotation produces a ZAMS distribution that has essentially no overlap with what is observed for field stars. There is, however, good agreement between the predicted and observed distributions if we assume that the rotation rate varies inversely with stellar radius as expected if radiative cores are decoupled from outer convective envelopes.

4. Summary

This paper provides for the first time an explanation for many of the details about the dependence of angular momentum and $<v \sin i>$ on mass that have been known for decades. These results also show the potential of using observations of angular momentum to test theories of the formation and early evolution of stars.

References

Behrend, R., Maeder, A. 2001, A&A 373, 190
Guenther, E. W., Lehmann, H., Emerson, J. P., Staude, J. 1999, A&A 341, 768
Hartmann, L. 2002, ApJ 566, L29
Herbst, W., Bailer-Jones, C.A.L., Mundt, R. 2001, ApJ 554, L197
Johns-Krull, C. M., Valenti, J. A., Koresko, C. 1999, ApJ 516, 900
Königl, A. 1991, ApJ 370, L39
Palla, F., Stahler, S. W. 1992, ApJ 392, 667
Rebull, L.M. 2001, AJ 121, 1676
Rebull, L.M., Wolff, S.C., Strom, S.E., Makidon, R.B. 2002, AJ 124, 546
Shu, F., Najita, J., Ostriker, E., Wilkin, F., Ruden, S., Lizano, S. 1994, ApJ 429, 781
Stahler, S. W. 1983, ApJ 274, 822
Swenson, F.J., Faulkner, J., Rogers, F. J., Iglesias, C. A. 1994, ApJ 425, 286
Wolff, S. C., Simon, T. 1997, PASP 109, 759

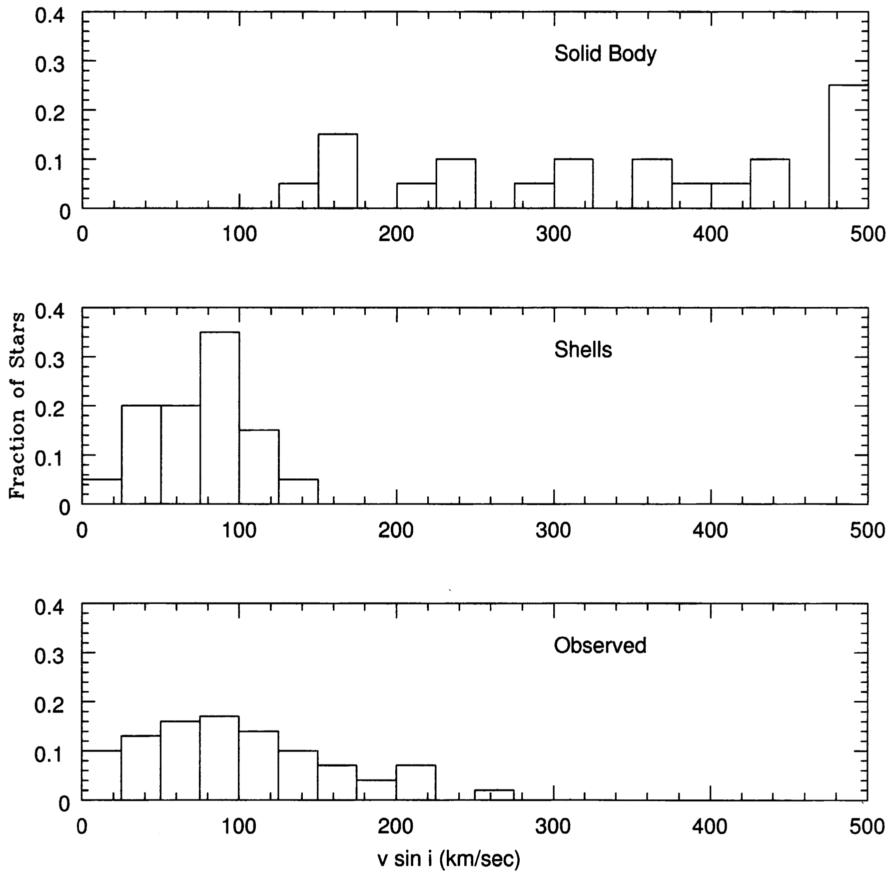

Figure 3. Observed and predicted ZAMS rotational velocities. The top panel shows the velocities expected on the ZAMS if the 20 stars on convective tracks in the current sample with M>1.3 $M_\odot$ (i.e., with masses above where main sequence braking due to winds sets in) conserve angular momentum as solid bodies during their subsequent evolution to the main sequence; the middle panel shows the predicted velocities if angular momentum is conserved in shells; the bottom panel shows the actual velocities for 69 field stars close to the ZAMS with masses in the range 1.5–2 $M_\odot$ taken from the study of Wolff & Simon (1997).