Observations of Accretion Disc-regulated Stellar Angular Momentum Evolution in Fully Convective Pre-main Sequence Stars

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Abstract. We re-address the theory of accretion disc-regulated angular momentum evolution for fully convective pre-main sequence stars in the Orion Nebula Cluster (ONC) and Taurus-Auriga. We gathered rotation periods from the literature, checking for previously identified source of bias, and re-calculated stellar radii in a consistent manner using recently updated spectral type estimations and newly established intrinsic colours, effective temperatures, and bolometric corrections for fully convective pre-main sequence stars. We find that disc-hosting stars (Class IIs) contain less specific stellar angular momentum than the disc-less stars (Class IIIs) which we interpret as indicating accretion disc-regulated stellar angular momentum evolution whereby the efficiency of this process is dependent on the lifetime of the accretion disc.

1. Introduction

Angular momentum conservation during contraction to the zero-age main sequence would result in stellar rotational velocities far exceeding break-up. Instead, stars must lose significant amounts of angular momentum during the first few Myr of formation in order to reproduce the observed rotation periods of accretion disc-hosts (e.g., Bouvier et al. 1986). Initial theories suggested that the differential rotation of the star and its Keplerian disc could provide a sufficient magnetic torque to efficiently brake the star (Camenzind 1990; Königl 1991). More recently, theoretical studies have favoured accretion-driven magnetised winds and outflows (Shu et al. 1994; Matt & Pudritz 2005; Zanni & Ferreira 2013) as possible mechanisms for angular momentum removal in pre-main sequence (PMS) stars.

From an observational perspective, the distribution of rotation periods for $\sim 1-5$ Myr old stars is observed to be bimodal (e.g. Edwards et al. 1993; Herbst et al. 2000; Herbst et al. 2002; Cohen et al. 2004; Lamm et al. 2005; Cieza & Baliber 2007; Davies et al. 2014). The peak of slower rotators indicates accretion disc-regulated stellar angular momentum removal whilst the peak of faster rotators indicates the spin-up of stars during contraction following the dispersal of their discs.

Here, we report on the distribution of specific stellar angular momentum for fully convective stars within the ONC and Taurus-Auriga. Detailed descriptions of the model we adopted for calculating the specific stellar angular momentum, $j_\star$, and how we imposed our fully convective limit are given in Davies et al. (2014). In Section 2., we summarise where we collected the data required to calculate $j_\star$ and in Section 3., we briefly discuss our results.

2. Stellar data

To calculate $j_\star$, we required rotation periods, stellar radii, and central densities (see Davies et al. 2014 for details). Photometrically determined rotation periods for stars within the ONC and Taurus-Auriga were gathered from the literature. We removed previously identified sources of bias from our final sample of rotation periods by checking for beats and aliasing as well as removing non-members and stars previously identified as binary or multiple systems. We calculated stellar radii, $R_\star$, using the Stefan-Boltzmann law ($R_\star \propto L_\star^{1/2}\, T_{\rm eff}^{-2}$). To do this, we required estimates of effective temperatures, $T_{\rm eff}$, and bolometric luminosities, $L_\star$, which were estimated using published spectral types, V- and Cousins $I_{\rm c}$-band or B- and V-band photometry, and the spectral type-to-$T_{\rm eff}$ conversions, bolometric corrections, and intrinsic colours for 5-30 Myr old PMS stars (Pecaut & Mamajek 2013). Although the ONC (~ 1 Myr; Hillenbrand 1997) and Taurus-Auriga (~ 2.8 Myr; White & Ghez 2001) are younger than 5 Myr, these PMS scales are more applicable than MS dwarf scales as they take into account the combined effects of the lower surface gravities and spotted surfaces of PMS stars.

To ensure our sample consisted solely of fully convective stars, we required estimates of stellar masses and ages. We assumed that the luminosity spreads observed in both the ONC and Taurus-Auriga are caused by real age spreads (see Davies et al. 2014 for a discussion) and use $T_{\rm eff}$ and $L_\star$ to calculate individual masses and ages using Siess et al. (2000) PMS model isochrone fitting. For each star above $0.35\,{\rm M}_\odot$, we determined the age at which it would form a radiative core, $t_{\rm core}$, and removed those with an isochronal age greater than $t_{\rm core}$.

Once stellar masses and ages had been calculated, stellar densities were interpolated from Siess et al. (2000) PMS core isochrones. These were then combined with the rotation periods and stellar radii to calculate $j_\star$.

2.1 Disc diagnostics

For our Taurus-Auriga sample, we were able to classify the PMS stars as disc hosting (Class II) or disc-less (Class III) using the results of detailed SED modeling available in the literature (Kenyon & Hartmann 1995; Andrews & Williams 2005; Luhman et al. 2010; Rebull et al. 2010). However, this information was not available for our ONC sample. Instead, we used Spitzer IRAC fluxes to classify stars in the ONC. Following the work of Prisinzano et al.(2008), we identified stars as Class III if $[2.2]-[3.6] < 0.5$, $[3.6]-[4.5] < 0.2$, $[4.5]-[5.8] < 0.2$, and $[5.8]-[8.0] < 0.2$ or if the star was detected in Cousins $I_{\rm c}$-band

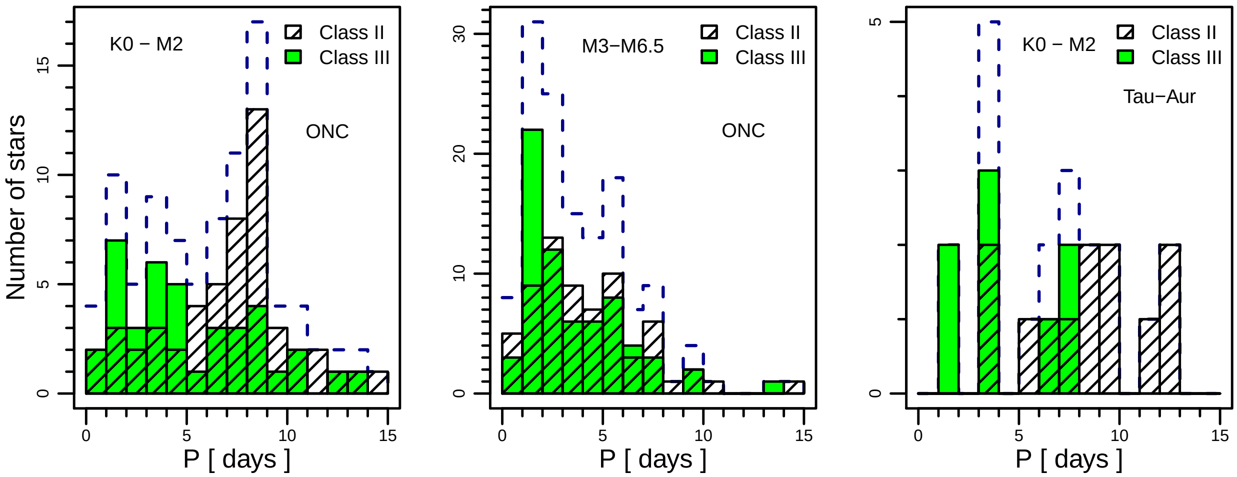

Figure .1: Rotation period distributions for the high mass ONC (left panel), low mass ONC (middle panel), and high mass (right panel) Taurus-Auriga stars. The full samples are shown as blue open-dashed columns, the Class II objects are shown as hatched columns, and the Class III objects are shown as green columns. The previously observed bimodal high mass and unimodal low mass distributions are recovered. Class II stars are observed to spin at slower rates than Class III stars and high mass ONC stars rotate slower than the low mass ONC stars.

but not at wavelengths longer than $3.6\,\mu$m. In addition, stars were identified as Class II if $[3.6]-[8.0]>1.0$, or $0.2<[3.6]-[4.5]<0.7$ and $0.6<[5.8]-[8.0]<1.0$ (Hartmann et al. 2005; Rebull et al. 2006). Any star that could not be identified as Class II or Class III using the criteria above was removed from our sample.

2.2 Mass segregation

We split our sample into two mass-segregated groups based on spectral type. The "high mass" stars are those of spectral type M2 or earlier and the "low mass" stars have spectral type later than M2, based on the work of Cieza & Baliber (2007). At the range of ages in our sample, this spectral type cut-off corresponds to a mass of $\sim 0.35\,\mathrm{M}_{\odot}$, the mass above which a star will develop a radiative core during its formation.

3. Results and discussion

Our final samples, consisting of 226 ONC and 24 Taurus-Auriga fully convective Class II and Class III stars for which we could calculate $j_{\star}$, are presented in Davies et al. (2014). These consisted of 91 ONC and 20 Taurus-Auriga stars of spectral type K0-M2 together with 135 ONC and 4 Taurus-Auriga stars of spectral type M3-M6.5.

Fig. .1 shows the rotation period distributions for the high mass ONC, low mass ONC, and high mass Taurus-Auriga samples. We recover the bimodal distribution previously seen for the high mass ONC stars and the unimodal distribution previously seen for the low mass

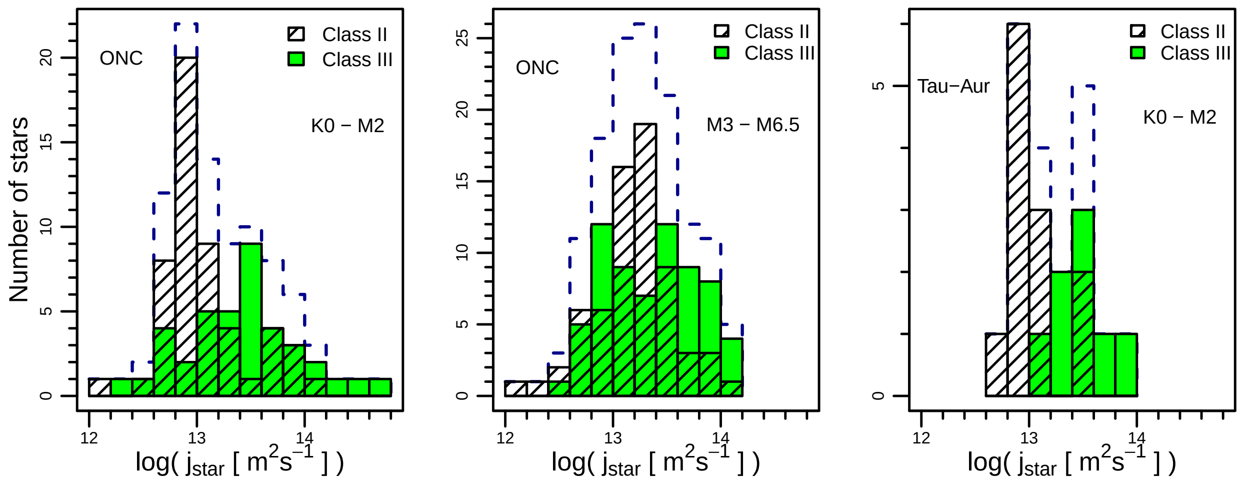

Figure .2: Distributions of $j_\star$ for the high mass ONC (left panel), low mass ONC (middle panel), and high mass (right panel) Taurus-Auriga stars. The colours of the columns are as in Fig. 1. Class II stars harbour less $j_\star$ than the Class IIIs with double-sided KS tests revealing that the probabilities of the Class II and Class III samples being drawn from the same parent population are 0.00045 (high mass ONC), 0.016 (low mass ONC), and 0.0086 (high mass Taurus-Auriga).

ONC stars (Herbst et al. 2002; Cieza & Baliber 2007). In all three samples the Class II stars rotate at a less rapid rate than the Class III stars. We interpret this as indicating accretion disc-regulated rotation during the Class II phase followed by spin up at constant $j_\star$ once the accretion disc has dissipated. However, we also observe slowly rotating Class III stars as well as more rapidly rotating Class II stars. The slowly rotating Class III stars have likely only recently been released from their discs and have not yet had time to spin up. In addition, the more rapidly rotating Class II stars are likely locked to regions of their Keplerian discs that are closer to their photospheres. This can be achieved if these stars have higher mass accretion rates and/or weaker dipole components of their large-scale magnetic fields such that their disc truncation radius is smaller (e.g. Adams & Gregory 2012).

This can also be extended to the lower mass stars. By comparing the left and middle panels of Fig. .1, we can see that the lower mass stars rotate faster than the higher mass stars. Donati et al. (2010) and Gregory et al. (2012) argue that these lower mass stars have more complex magnetic fields which would shorten their disc truncation radii. Thus, stars later than M2 would be locked to faster-spinning regions of their Keplerian discs than stars earlier than M2.

In Fig. .2 we show the distributions of $j_\star$ for the high mass ONC and Taurus-Auriga samples and the low mass ONC sample. In each of the three samples, the Class II stars contain less $j_\star$ than the Class III stars. If we assume that, during the Class II phase, the star experiences a spin-down torque, $j_\star$ would decrease with time. However, if this torque is provided by an interaction between the star and the disc, once the accretion disc has dissipated, $j_\star$ will evolve at a constant rate and the star will spin up as it continues to contract towards the main sequence. The Class III stars in our sample must have had shorter lived accretion discs and have thus spent a fraction of their lifetimes evolving at constant $j_\star$. Meanwhile, the Class II stars have continued to lose $j_\star$. Thus, our observations suggest that the efficiency of the accretion disc-regulated angular momentum removal process is dependent on the lifetime of the accretion disc.

If we just focus on the Class III sample, we find that the youngest Class IIIs contain less $j_\star$ than the older Class IIIs. At the same time, we find that the ages of our Class II and Class III samples are consistent, such that disc dispersal occurs at a variety of ages. On average, the youngest of these Class IIIs would have had the shortest disc lifetimes in order to be observed as purely photospheric whilst the older Class IIIs do not necessarily need to have had such short disc lifetimes. Instead, on average, they would have experienced a spin down torque for longer than their younger Class III counterparts. Again, this highlights the dependence of angular momentum removal efficiency on disc lifetime.

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