Magnetic Fields throughout Stellar Evolution
Proceedings IAU Symposium No. 302, 2013
P. Petit, M. Jardine & H. Spruit, eds.

doi:10.1017/S1743921314001793

Angular momentum evolution of young stars

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Abstract. In recent years, rotation periods for large numbers of pre-main-sequence stars have become available, covering a wide range of ages and star forming environments. Simultaneously, theoretical developments in the physics of the star-disc interaction have been carried out, and observational measurements of the magnetic field geometry of both fully convective, and pre-main-sequence stars have become available. This review discusses these recent developments, and the extent to which the observational data fits within the existing theoretical frameworks.

Keywords.

1. Introduction

If the protostellar collapse process was dominated by gravity, one would expect to see pre-main-sequence (PMS) stars rotating at close to their breakup velocities. However, initial studies of rotational velocities in PMS stars revealed typical rotation rates below 40 $\mathrm{km\,s^{-1}}$, around one-fifth of the breakup velocity (Vogel & Kuhi 1981; Bouvier, Bertout, Benz *et al.* 1986; Hartmann, Hewett, Stahler *et al.* 1986). This finding is even more puzzling when one considers that these stars are accreting material from their circumstellar disc which carries with it large amounts of specific angular momentum. If accretion is sustained at moderate rates for a few Myr, even a slowly rotating star will be spun up to more than half it's breakup velocity (Bouvier 2013). The slow rotation rates of pre-main-sequence stars therefore requires a mechanism which efficiently removes angular momentum from the central star.

Using a model first developed for accreting neutron stars (Ghosh & Lamb 1979), Koenigl (1991) was first to suggest that the magnetic interactions between the inner disc and the magnetic field of the star could efficiently extract angular momentum. Very shortly thereafter, evidence for a correlation between rotation rate and accretion was revealed (Edwards, Strom, Hartigan *et al.* 1993; Bouvier, Cabrit, Fernandez *et al.* 1993). The correlation revealed that accreting young stars rotated more slowly, on average, than non-accreting stars, providing strong observational support for Koenigl's framework. This review looks at how theoretical and observational breakthroughs have affected this picture in the intervening twenty years. We start by examining the support for the disc locking framework, as set out by (Koenigl 1991).

1.1. *The disc locking framework*

The calculation of torques on the star, exerted by magnetic field lines anchored to the star and connected to the disc has been carried out by many authors (e.g. Ghosh & Lamb 1979; Lovelace, Romanova & Bisnovatyi-Kogan 1995; Wang 1995; Yi 1995; Armitage & Clarke 1996; Rappaport, Fregeau & Spruit 2004). These models are quite similar in the whole. Here we use the prescription developed by Matt & Pudritz (2005), which itself follows Armitage & Clarke (1996) - see figure 1. The star's magnetic field connects to the disc between radii R_t and R_{out}. The rotation rate of the disc differs from that of

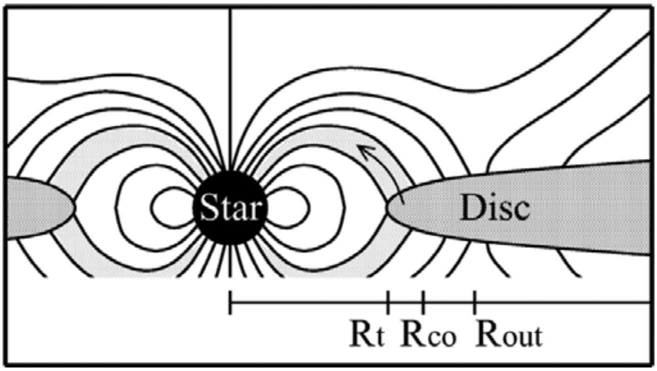

Figure 1. Magnetic star-disc interaction under the disc-locking framework. The stellar field connects to the accretion disc between radii R_t and R_{out}. The stellar field dominates the accretion flow onto the star (arrow). Taken from Matt & Pudritz 2005.

the star at all radii, except at R_{co}, the co-rotation radius. For $r < R_{co}$ the disc rotates faster than the star, whilst for $r > R_{co}$ the star rotates faster than the disc. At all radii in the disc apart from R_{co}, differential rotation twists the field azimuthally. Inside R_{co}, the field lines are twisted so that they lead the star. Torques from this region spin the star up. Outside R_{co}, the field lines are twisted so that they trail the star. Torques from this region spin the star down. In certain circumstances, this can lead to an equilibrium situation, any increase in stellar spin would move R_{co} inwards, increasing the spin-down torques, and vice-versa. This is the disc-locking framework as put forward by Koenigl (1991). How well does it hold up against modern observational results?

2. Rotation rates of pre-main-sequence stars

The pioneering works on early stellar rotation focused on measurement of projected rotational velocities. However, the development of large-format CCDs in the mid 90's allowed large scale photometric monitoring campaigns that provided rotational period distributions for thousands of low-mass stars in the PMS stage, across a wide range of masses, ages and environments. Reference lists for most of the available studies are available in the excellent reviews of Irwin & Bouvier (2009) and Bouvier (2013). Figure 2 (from Irwin & Bouvier 2009) shows a sample of some of these results.

From the extensive rotation rates in the literature, some clear trends have emerged. At very young ages ($\sim$ 1 Myr) the initial distribution is very broad, with rotation periods typically spanning the range 1–10 days at all masses. For stars more massive than $M > 0.3M_{\odot}$ the period distribution is bi-modal, with peaks at 2 and 8 days (Herbst, Bailer-Jones & Mundt 2001). For lower masses the distribution is still broad, but is unimodal with a peak around 2 days. During early PMS evolution (1–5 Myr) there is little evolution in period for the higher-mass objects, despite the contraction of these stars towards the main sequence, whilst the lowest mass objects spin up significantly. Furthermore, this spin-up is mass dependent - indeed, Henderson & Stassun (2012) have suggested the period-mass slope for lower mass stars can be a useful age indicator for very young clusters.

At later stages of evolution the period distribution is flat over the range 0.5–1 $M_{\odot}$. This is shown most clearly in the period distribution for the 13 Myr old h-Per association (Moraux, Artemenko, Bouvier *et al.* 2013). In spite of the fact that stellar contraction towards the main sequence is continuing, the slow rotators still show periods in the

https://doi.org/10.1017/S1743921314001793 Published online by Cambridge University Press

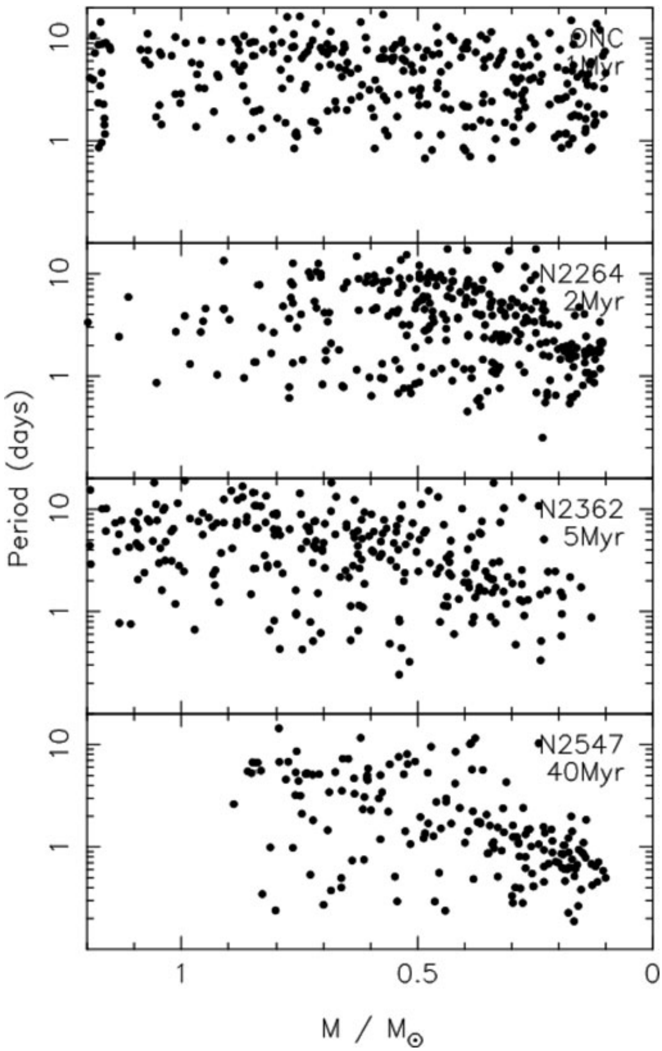

Figure 2. Compilation of rotation periods for young stars with masses $M \leqslant 1.2M_{\odot}$. References for the original studies can be found in Irwin & Bouvier 2009.

range 8–10 days, whilst the most rapid rotators have spun up to 0.2–0.3 days. This later evolution is reasonably well described by the combined effects of magnetic stellar wind braking and core-envelope decoupling for the slow rotators, which explains the lack of spin-up of the slow rotators by hiding angular momentum in their cores. For a more detailed review of later evolution, we refer the reader to the review of Bouvier (2013). Instead, we focus on explaining the very early evolution, and the origin of the period distribution at ~ 1 Myr.

2.1. *The link between discs and rotation rate*

If the star-disc interaction is responsible for the slow rotation of PMS stars, a correlation between discs and rotation is expected. Despite very early confirmation of this correlation (Edwards *et al.* 1993; Bouvier *et al.* 1993), this area remained controversial for nearly ten years. This was largely due to some studies (e.g. Littlefair, Naylor, Burningham *et al.* 2005) finding no correlation between rotation and the presence of a disc. The situation

https://doi.org/10.1017/S1743921314001793 Published online by Cambridge University Press

improved dramatically with surveys of disc presence from the Spitzer space telescope, which gave much more robust indicators of disc presence. Repeated studies using reliable disc indicators and large sample sizes (e.g. Rebull, Stauffer, Megeath *et al.* 2005; Cieza & Baliber 2007; Dahm, Slesnick & White 2012; Affer, Micela, Favata *et al.* 2013) found clear indication of a disc-rotation correlation, in the sense that stars with discs rotate more slowly than those which do not. This has led to general consensus that some mechanism related to the presence of an accretion disc is responsible for the slow rotation of PMS stars. In the next section, I present arguments why this mechanism cannot be disc-locking, but first I outline some of the observational challenges and uncertainties which affect the picture presented above.

2.2. *Caveats*

The rotational evolution of young stars has been understood largely through the period-mass diagrams for clusters with a range of ages. The ages of young stars in particular are subject to large, and possibly systematic, uncertainties (see e.g. Bell, Naylor, Mayne *et al.* 2013). In addition, it is not clear that applying a single age to a young cluster is appropriate. Whilst the interpretation of luminosity spreads in young clusters as age spreads is controversial (e.g. Jeffries, Littlefair, Naylor *et al.* 2011; Baraffe, Vorobyov & Chabrier 2012; Hartmann, Zhu & Calvet 2011; Hosokawa, Offner & Krumholz 2011), it is certainly true that some clusters with rotational studies could be composed of multiple stellar populations. A good example of this is Cepheus OB3b, which has two separate sub-clusters which may have different ages (Allen, Gutermuth, Kryukova *et al.* 2012). This may explain the difference in the period-mass diagram between Cepheus OB3b and the similarly aged cluster NGC 2362, which has also been ascribed to environmental differences between the two clusters (Littlefair, Naylor, Mayne *et al.* 2010).

One might expect the photometric period to be the most accurately determined of these quantities, and this is largely true. However, even here caution is advised. The majority of studies to date are ground based and suffer from gaps in coverage due to the day-night cycle and bad weather. One cluster where this is not true is NGC 2264, where a 28 day continuous monitoring campaign was carried out by the COROT satellite. Affer *et al.* (2013) present rotational periods from this campaign, and show that around 20% of periods from the previous ground based studies were unreliable. Moreover, even when a photometric period is reliably detected, it may not be due to the rotation of the young star (e.g. Artemenko, Grankin & Petrov 2012). Other sites of emission in the star-disc system (e.g. the inner rim of the accretion disc) can potentially give rise to periodic variability. By using their unbroken lightcurves to make subjective decisions about the origin of variability, Affer *et al.* (2013) estimate that 10% of all PMS stars in NGC 2264 show periodic variability from obscuration by the inner disc. Amongst stars with discs, this fraction rises to 35%, raising serious concerns about biasses in photometric samples. However, Affer *et al.* (2013) also found that the link between rotation and discs is still present, even after this contamination is removed.

3. Challenges to disc locking

In the disc locking picture, torques from the twisted field lines transfer angular momentum from the star to the disc. Theoretical challenges to this picture means that is unlikely to be the cause of slow rotation in young stars.

If we define the degree of twisting $\gamma = \frac{B_\phi}{B_z}$ then γ itself is a function of the rate at which the magnetic field slips through the disc. Matt & Pudritz (2005) parameterise the field slippage with a diffusion parameter $\beta \equiv \frac{\eta_t}{h\nu_k}$, where η_t is the effective magnetic diffusivity, h is the disc thickness and ν_k is the Keplerian velocity. For high values of

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β, the field slips through the disc and γ is small, leading to small torques on the star. As β falls, the degree of twisting, and the torque, increases. However, a critical value of the field twist, $\gamma_c \approx 1$, exists, beyond which the field lines inflate and open (e.g. Aly 1985; Lovelace *et al.* 1995). At this point they can no longer transfer angular momentum between the star and the disc. Therefore, for small values of $\beta \sim 0.01$, the field is well coupled to the disc which leads to significant opening of the field lines and a *reduction* in the star-disc torques. Matt & Pudritz (2005) show that the maximal torque actually occurs for $\beta \approx 1$, representing significant slippage of the magnetic field through the disc.

For the disc locking model, the equilibrium spin rate can be written as

$$\Omega_{eq} = C(\beta, \gamma_c) G^{5/7} M_*^{5/7} \dot{M}_a^{3/7} \mu^{-6/7}, \tag{3.1}$$

where $\mu = BR^3$ is the stellar magnetic moment, M is the stellar mass, $\dot{M}_a$ is the accretion rate and C is a dimensionless constant. For the disc locking model to explain the rotation rates seen in PMS stars requires C to be of order unity, and hence $\beta \sim 1$. This is problematic, since in realistic accretion discs we expect $beta \sim 0.01$, which reduces the spin-down torque by two orders of magnitude (Matt & Pudritz 2005). These simple theoretical arguments are supported by detailed 2D simulations (e.g. Zanni & Ferreira 2009).

Of course, a star may not necessarily reach spin equilibrium. To calculate the rotation period of a star at 1 Myr, it is necessary to follow the full evolution, taking account of the spin-down torques from the star disc interaction, the angular momentum accreted from disc material, and the contraction of the star towards the main sequence. This calculation has been performed (Matt, Pinzón, de la Reza *et al.* 2010). The end result is that for $\beta \sim 1$, the star-disc torques are strong, and the stellar spin is close to the equilibrium values, which range from 1–10 days at 1 Myr. For realistic values of $\beta \sim 0.01$, the star-disc torques are weak; instantaneous spin rates differ greatly from the equilibrium values, and rotation rates at 1 Myr range from 0.6–2 days. In short, disc locking is not expected to operate in physically realistic accretion discs.

Disc locking faces observational challenges as well. For all stars in a disc-locked state, the truncation radius of the accretion disc is close to the co-rotation radius (e.g. Matt & Pudritz 2005). Le Blanc, Covey & Stassun (2011) found that this does not hold for the young stars of IC 348, with many slow rotators having truncation radii larger than the co-rotation radius, and no obvious difference in truncation radii between slow and fast rotators. It is worth mentioning, however, that measuring the truncation radius of the accretion disc is not easy (e.g. Carr 2007; Pinte, Ménard, Berger *et al.* 2008). Perhaps more seriously for disc-locking, Littlefair, Naylor, Mayne *et al.* (2011) found a link between stellar radius and rotation in four young associations, in the sense that the slow rotators were, on average, smaller than the fast rotators. The stellar radius enters equation 3.1 for the equilibrium period through the magnetic moment, such that $P_{eq} \propto R^{2.5}$. Therefore, the observed correlation is in the opposite sense to that expected under disc locking. It is also in the opposite sense to that expected if the young stars shrink with age, and spin up as they are released from disc locking. In conclusion, it is both theoretically and observationally unlikely that the slow rotation rates seen in PMS stars are explained by disc locking, i.e. the transfer of angular momentum between the star and the disc along closed field lines.

4. Alternatives to disc locking

The challenges faced by disc locking have led different groups to examine alternatives in which outflows along open field lines remove angular momentum from the star-disc

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system as a whole. These outflows fall into three main categories: winds from the accretion disc (the X-wind), accretion-powered stellar winds, and magnetospheric ejections. For a fuller review of the different mechanisms, see Ferreira (2013).

4.1. *Disc Winds*

In considering the impact of disc winds on the spin evolution of young stars, we can neglect extended, magnetised, disc winds (e.g. Blandford & Payne 1982; Ferreira 1997). This is because such winds are not causally connected to the star and thus cannot extract angular momentum from it (Ferreira 2013). The same is not true of the X-wind model (Ostriker & Shu 1995), originally proposed with the twin aims of explaining both the presence of jets around PMS stars and the slow stellar rotation within single theory. This model shares some similarities with the disc-locking model; again, the accretion disc is truncated just inside the co-rotation radius. However, it is assumed that the magnetic pressure forces a narrow region straddling the co-rotation radius, the X-region, to rotate as a solid body at the stellar rotation rate. Material just inside the x-region sub-rotates and threads easily onto inward-leaning field lines and is accreted onto the star. Material just outside super-rotates and threads easily onto outward-leaning field lines, escaping in a wind. Torques from the accretion funnels transfer angular momentum to the disc material, forcing it outwards, whilst torques from wind extract angular momentum from the disc material, forcing it inwards. Thus the material is 'pinched' into the X-region, causing truncation of the disc. As a result, much or all of the angular momentum of the accretion flow is transferred to the wind, allowing the star to maintain slow rotation.

Recent work on the X-wind model has extended it to non-dipolar field configurations (Mohanty & Shu 2008) and these models can re-create the observed stellar spin rates in the few cases where the magnetic and accretion properties are measured well enough to allow a comparison (V2129 Oph and BP Tau; Donati, Jardine, Gregory *et al.* 2007, 2008). However, the X-wind model does face theoretical and observational challenges. For example, detailed MHD simulations of the star-disc interaction have never produced X-winds, although it is not clear that they would have been expected, given the way the simulations were set up (Ferreira 2013). Observationally the X-wind model also predicts disc truncation near the co-rotation radius, which is not observed (Le Blanc *et al.* 2011), and jet kinematics of young stars are not consistent with predictions from the X-wind model (Ferreira, Dougados & Cabrit 2006; Cabrit 2007).

4.2. *Accretion Powered Stellar Winds*

Stellar winds, as opposed to winds from the accretion disc, may be a significant contributor to the outflows from PMS stars (e.g. Fendt, Camenzind & Appl 1995; Hirose, Uchida, Shibata *et al.* 1997; Romanova, Ustyugova, Koldoba *et al.* 2009). Provided the outflow rate is high enough, the stellar winds can also extract enough angular momentum to explain the slow rotation rates of PMS stars (e.g. Hartmann & Stauffer 1989; Matt & Pudritz 2005). By following the full evolution of an accreting PMS star, including accreted angular momentum and contraction towards the main sequence, Matt, Pinzón, Greene *et al.* (2012) showed that the rotation rates observed at $\sim$1 Myr can be explained by a stellar wind, provided that the outflow rate is approximately 10% of the accretion rate. To obtain these high outflow rates, Matt & Pudritz (2005) suggested that a fraction of the potential energy from the accreted matter was used to drive an accretion powered stellar wind. There is some evidence for this; some emission lines in PMS stars are best explained by stellar wind kinematics, and they generally correlate with accretion rates (e.g. Johns-Krull 2007; Kurosawa, Romanova & Harries 2011). However, questions remain as to whether PMS stars have enough accretion power to drive such strong outflows (Zanni & Ferreira 2011), or as to how the accretion power is used to drive the wind. Matt & Pudritz (2008) suggested that waves generated in the photosphere by the impact at the base of the accretion funnels could transport energy to the open field lines, where it would drive enhanced MHD activity which in turn drives a stellar wind. Such a mechanism has been studied in a simplified, 1D environment by Cranmer (2008), who found that outflow rates only reached around one percent of the accretion rate, not enough to significantly affect the rotation of the PMS star.

4.3. *Magnetospheric Ejections*

As we saw in section 3, differential rotation between the star and disc leads to the opening of field lines, limiting the effectiveness of disc locking. However the inflation, opening and reconnection of these field lines means that we expect to see magnetospheric ejections in PMS stars. These magnetospheric ejections may regulate stellar angular momentum in two ways; not only do they exert a braking torque directly on the star, but they also carry angular momentum from the disc, thus reducing the spin-up torque from accretion. In fact, the combination of magnetospheric ejections and a stellar wind can exert a net spin-down torque on the star (Zanni & Ferreira 2013). The extreme limit of magnetospheric ejections are propeller phases, when the magnetic field disrupts accretion entirely and drives outflow from the star-disc system (e.g. Romanova, Ustyugova, Koldoba *et al.* 2005; D'Angelo & Spruit 2011). Propeller phases can exert strong spin-down torques on the central star. Whilst simulations of magnetospheric ejections and propeller phases are promising, it is unknown if, in practise, they occur with sufficient frequency to have a significant effect on the stellar rotation . The simulations of Zanni & Ferreira (2013) require strong kilo-Gauss dipolar fields and it is not clear if these are common amongst PMS stars (e.g. Donati *et al.* 2008; Donati, Skelly, Bouvier *et al.* 2010). Meanwhile, no observational evidence exists for a PMS star in a propeller phase.

5. Summary

It is clear that disc locking does not explain the slow rotation of PMS stars; opening of field lines in realistic star-disc systems means that the torques on the star are too small. Whilst several alternative descriptions of the star-disc interaction can in principle provide significant spin-down torques, it is not clear if any of them can successfully spin down PMS stars to rotation periods of 10 days at ~ 1 Myr, or maintain slow rotation for the next few Myr. It is of course quite possible that some or all of these mechanisms act in concert to spin down the star (Ferreira 2013). Possibly, modifications to the theories above, such as and X-wind where the stellar and disc magnetic fields interact (Ferreira, Pelletier & Appl 2000) could be more efficient.

Littlefair *et al.* (2011) put forward a more radical, and speculative, hypothesis. The need for a spin-down torque during the PMS phase is driven by the absence of spin up for slowly rotating PMS stars between 1–5 Myr. Since these stars are believed to be contracting towards the main sequence, and are fully convective, this implies angular momentum loss from the stars. Littlefair *et al.* (2011) show, however, that the slowly rotating stars are also the smallest in any given cluster. The cause of radius spreads in young clusters is highly controversial. It may reflect a spread in ages, but it may also be caused by the effects of accretion driving stars from thermal equilibrium (e.g. Baraffe *et al.* 2012; Hartmann *et al.* 2011; Hosokawa *et al.* 2011). If the latter is true, then the small, slowly rotating PMS stars in young clusters will not contract significantly between 1–5 Myr, and the need for an efficient spin-down torque during this phase is dramatically reduced. Of course, this picture does not explain the slow rotation of stars at ~ 1 Myr and so one, or all, of the processes above will still be needed at earlier phases, when the young star was still embedded. The importance of the star-disc interaction during the embedded phase would explain the present day link between discs and rotation as a 'fossil' of earlier processes.

One question which remains unanswered is the origin of the large spread in rotation rates at 1 Myr, with stars in the ~ 1 Myr Orion Nebula Cluster showing an order of magnitude spread in rotation rate, corresponding to four orders of magnitude in angular momenta. This wide spread in initial rotation rates probably reflects processes occurring during the embedded phase. For example, Gallet & Bouvier (2013) suggest that variations in the protostellar disc mass could lead to a wide dispersion in angular momenta. Another question, perhaps linked to the wide spread in rotation rates, is the origin of the bi-modality seen in the Orion Nebula Cluster. One possibility, which has been only briefly explored, is the effects of varying geometries in the stellar magnetic field (e.g. Morin, Donati, Petit *et al.* 2010; Gregory, Donati, Morin *et al.* 2013; Gastine, Morin, Duarte *et al.* 2013). There is no doubt that many of the processes described above will behave differently for fields which are dominantly dipolar, compared to fields dominated by e.g. octopolar components. As an example, Batygin & Adams (2013) find that the accretion torque for a star with a predominantly octopolar field is an order of magnitude lower than for a dipolar field.

The last ten years has has seen tremendous development in our understanding of the processes governing the rotation of young stars. We now recognise that disc locking cannot be effective, and have a number of plausible alternative theories which may present a solution. In parallel we have also reached a firm conclusion regarding the link between rotation and the presence of accretion discs, and have a new observational constraint, in the observed link between stellar rotation and radius. Coupled with advances in our knowledge of the magnetic field geometries of young stars it is hoped that the next ten years will bring new understanding of the processes responsible for the slow rotation of pre-main-sequence stars.

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https://doi.org/10.1017/S1743921314001793 Published online by Cambridge University Press