Stellar spindown: From the ONC to the Sun

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Abstract. Rotation is a key parameter in the evolution of stars. From 1 Myr (the age of the ONC) to 4.5 Gyr (the age of the Sun), solar-like stars lose about 1-2 orders of specific angular momentum. The main agents for this rotational braking are believed to be star-disk interaction and magnetically powered stellar winds. Over the last decade, the observational fundament to probe the stellar spindown has dramatically improved. Significant progress has been made in exploring the underlying physical causes of the rotational braking. Parameterized models combining the effects of star-disk interaction, winds, and pre-main sequence contraction are able to reproduce the main features of the rotational data for stars spanning more than 3 orders of magnitude in age. This has allowed us to constrain stellar ages based on the rotation rates (‘gyrochronology’). One main challenge for future work is to extend this type of analysis to the substellar mass range, where the rotational database is still sparse. More theoretical and observational work is required to explore the physics of the braking processes, aiming to explain rotational evolution from first principles. In this review for Cool Stars 15, I will summarize the status quo and the recent developments in the field.

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INTRODUCTION

Analysing the spindown of low-mass stars is one of the most notorious and difficult issues in astrophysics. We are dealing with a multi-faceted problem: The spin of stars is a function to fundamental stellar properties – mass, radius, age. The rotation rate is also affected by the star formation process, including the collapse of molecular cloud cores, the formation of binaries and planetary systems, and accretion from circumstellar disks. Finally, the stellar magnetic field, its generation, structure and interaction with the stellar atmosphere plays a dominant role for the regulation of the rotation from the T Tauri phase to the age of the Sun. A comprehensive discussion of the spindown of stars thus requires input from a broad range of fields. While I will mostly focus on rotation itself, I encourage the reader to explore related chapters in this volume, for example the reviews by Edwards, Donati, Küker, Stelzer, Basri, as well as the splinter session summary by Reiners et al..

In this review, I will trace the spin of stars from ~ 1 Myr, the age of the Orion Nebula Cluster, to 4.5 Gyr, the age of the Sun. In this time frame, the angular momentum of stars is primarily controlled by two mechanisms: 1) Disk braking, used here as a generic term for mechanisms that remove angular momentum from the star via the interaction between star and disk, including disk-locking and accretion-powered stellar winds. 2) Wind braking, i. e. angular momentum losses due to magnetized stellar winds.

While disk braking operates on relatively short timescales compatible with the disk lifetime of 1-10 Myr, wind braking is a long-term process and regulates the spindown on
timescales of hundreds of Myr. This allows us to discuss the two processes separately: In the first part of this review, the focus will be on disk braking, i.e. the evolution in the pre-main sequence phase. In the second part, wind braking will be discussed by investigating the long-term evolution on the main-sequence. I will focus on objects with masses ranging from about one solar mass down to the substellar regime.

Reviewing the rotational evolution of stars and brown dwarfs is a timely exercise, for two reasons:

1) We have recently experienced an enormous growth in the number of objects with known periods, covering a wide range of ages and masses. Rotation rates are traditionally measured using two techniques, photometric monitoring providing rotation periods and high-resolution spectroscopy providing projected rotational velocities $v \sin i$ from Doppler line broadening. Thanks to the availability of wide-field imagers at 2-4 m class telescopes as well as the exploitation of planetary transit survey, the rotational database now comprises periods for about 3000 objects, and counting. In addition, the availability of high-resolution multi-object spectrographs (e.g., FLAMES at the VLT) has significantly enlarged the pool of $v \sin i$ data.

2) A number of new developments over the past five years have enabled studies that provide important complementary insights. Examples are the availability of the Spitzer telescope for mid-infrared studies of disk braking (see contribution by Baliber, this volume) and the ongoing efforts to determine magnetic field structures from Zeeman Doppler Imaging (see review by Donati, this volume). Combining the rotational data with these additional information yields a new, comprehensive picture of the angular momentum evolution of stars.
PRE-MAIN SEQUENCE EVOLUTION

Initial period distribution

The initial distribution of rotation rates of low-mass stars is now well-established, thanks to extensive survey work in clusters at 1-2 Myr, mainly the ONC and NGC2264. For a detailed discussion of the available data in these two clusters see for example Stassun et al. [51], Herbst et al. [15, 14], Rebull [38], Makidon et al. [25], Lamm et al. [24, 23]. Fig. 1 shows the period distribution in the ONC and NGC2264, as published by Lamm et al. [23]. Three features in these histograms should be highlighted: a) At this early age, the objects show a broad range of periods, mostly between 1 and 10 d with a tail extending to \( \sim 20 \) d. b) The median period drops with decreasing object mass in the considered mass range. c) The distribution is bimodal for solar-mass stars, but unimodal for very low mass stars (see the review by Herbst et al. [12]).

As of today, the datasets in the ONC and NGC2264 do not include the lowest mass stars and brown dwarfs (but see the contribution by Rodriguez-Ledesma in this volume for an update). In general, the period database for substellar objects is sparsely populated. Nonetheless, the available data allows us first important conclusions. In Fig. 2 we show periods for objects with masses of 0.02 to 0.3 \( M_\odot \) in the \( \sim 5 \) Myr old \( \epsilon \) Ori region.

As can be seen in this plot, the trend of declining median period towards lower masses, as seen in the ONC, continues steadily in the substellar regime. As a result, the median period for brown dwarfs is shorter than one day, and the fast rotators in this mass regime are at periods of 3-5 h (Bailer-Jones & Mundt [1], Zapatero Osorio et al. [53], Scholz & Eislöffel [45, 43]). These rotation rates are comparable to the breakup limit, the value where centrifugal and gravitational forces are in balance at the equator.

Disk braking at 1-5 Myr

The first 5 Myr in the spin evolution are characterized by strong rotational regulation. This has been firmly established in a number of recent studies, based on the growing rotational database in young open clusters and star forming regions (e.g. Tinker et al. [52], Rebull et al. [37], Rebull et al. [36], Lamm et al. [23], Herbst & Mundt [13], see also the review in Herbst et al. [12]). A good illustration of this finding is given in Fig. 3. The average \( v\sin i \) at 1-5 Myr is clearly inconsistent with angular momentum conservation; instead it roughly follows the trend expected for angular velocity (hence period) conservation. This can be understood as a consequence of a rotational braking mechanism affecting a fraction of the objects that decreases with age. The maximum timescale for this type of regulation is \( \sim 5 \) Myr, consistent with the lifetime of accretion disks, a first indication that the braking mechanism is related to the presence of a disk.

In fact, this is the underlying assumption in the most commonly discussed scenarios for the strong rotational regulation in the T Tauri phase (called 'disk braking' in the following). The theories for this mechanism essentially fall in two groups: Either the angular momentum is extracted directly from the star, or it is transferred from the star to the disk. 'Disk-locking’ is probably the leading idea here: According to the standard
picture (Camenzind \cite{5}, Koenigl \cite{21}), star and disk are coupled by the strong stellar magnetic field. As a result, the disk exhibits a torque onto the star, and thus slows down its rotation. Angular momentum is moved from the star to the disk and then carried away in a disk wind. One possible realization of a disk-locking scenario is the X-wind model (e.g., Shu et al. \cite{4}, Mohanty & Shu \cite{31}).

Alternative models for disk braking are based on stellar winds. A solar-type wind as in main-sequence objects, however, would not be sufficient for the strong braking seen in T Tauri stars. This leads to the idea of stellar winds powered by accretion. Matt & Pudritz \cite{2} have demonstrated that accretion-driven winds can in principle explain the observational picture, if the mass outflow rates are a substantial fraction of the accretion rates ($\sim 10\%$).

For observational studies of disk braking, it is important to point out that both types of models – accretion-powered winds and disk-locking – require the presence of a disk and a coupling between star and disk. Thus, observations should primarily aim to establish whether a connection between disk and rotation is present or not. Edwards et al. \cite{10} have presented first evidence for such a connection, in the sense that objects with near-infrared colour-excess, indicative of an inner disk, are primarily seen as slow rotators. While some studies have confirmed this early finding (e.g., Herbst et al. \cite{14}), others did not (e.g., Stassun et al. \cite{50}).

The mid-infrared observations from the Spitzer Spacecraft Telescope, launched 2003, have greatly improved our understanding of circumstellar disks. For the first time, Spitzer provides unambiguous and reliable disk indicators for the large numbers of objects in the ONC and NGC2264 with measured rotation periods. Based on Spitzer
FIGURE 3. Average log ($v_{\sin i}$) vs. log $R$ for young stars. The points with error bars in both directions are the average log ($v_{\sin i}$) for all stars within the specified range in log $R$. The log ($v_{\sin i}$) values for many individual clusters are also plotted. Approximate ages as a function of $R$ are indicated. The solid line shows the best linear fit, excluding the datapoint at 10 Myr. The dashed lines are the relations expected for evolution with constant angular velocity (slope of 1), and constant angular momentum (slope of $-1$). The observed slope is within 2$\sigma$ of the prediction for constant angular velocity, but inconsistent with the value expected for conservation of angular momentum. Figure from Rebull et al. [36].

Data, Rebull et al. [35] indeed find strong evidence for disk braking: The overwhelming majority of the objects with disks are slow rotators with periods $> 1.8$ d. A similarly clear result has been obtained for NGC2264 by Cieza & Baliber [6]. It is probably fair to say that most the researchers working in the field today believe that the presence of a disk clearly plays a role for the rotational braking.

On the other hand, negative results regarding disk braking have been obtained for IC348 (age 2-4 Myr, Cieza & Baliber [7]), Taurus, and Chamaeleon I ($\sim 2$ Myr, Nguyen et al., in prep.). We are still looking at partly controversial findings, possibly pointing at environmental differences. A number of aspects can dilute a signature of disk braking, e.g., age spread, binarity, dispersion in disk lifetimes, or insufficient sample size. If and how these factors can explain all the observational results is currently under investigation (see the contribution by Baliber, this volume). In standard disk braking scenarios it is not the mere presence of a disk, but the coupling between star and disk that provides the angular momentum removal. Thus, a more detailed understanding requires to look at a variety of disk braking diagnostics, including emission lines affected by accretion and winds (see review by Edwards, this volume).

Another open issue is the mass dependence of this mechanism, which can be probed
by looking at the very low mass objects in star forming region. Studies of disk braking in brown dwarfs are rare, mainly due to a lack of overlap of period and Spitzer data. The few existing constraints, however, indicate that disk braking is at work in substellar objects as well (Scholz & Eislöffel [45], Mohanty et al. [32]). However, the signature of disk braking, as seen in Spitzer data, becomes weaker at very low masses (Rebull et al. [35]), pointing to 'imperfect' disk braking (Lamm et al. [23]). This might be explained by a mass dependency in the magnetic field topology and will be subject of future programs.

MAIN-SEQUENCE EVOLUTION

The pre-main sequence transition

The rotational picture in the age range 10-100 Myr is difficult to interpret, because we see superimposed the effects of disk braking, the strong pre-main sequence contraction, as well as the beginning of wind braking. In a recent paper, however, we have shown that the median $\nu \sin i$ for stars covering ages from 5 to 30 Myr is inconsistent with the expected evolution for angular velocity conservation, but roughly in agreement with angular momentum conservation (Scholz et al. [41]). This is in stark contrast to the behaviour at 1-5 Myr, as discussed above (see Fig. 3), indicating a sharp change in the rotational braking at 5-10 Myr. This is readily explained by the disk dissipation, causing the breakdown of disk braking, resulting in rapid spinup due to the contraction.

Including rotational data at $\sim$ 100 Myr shows the onset of wind braking: The median rotation rates are significantly lower than expected from pure angular momentum conservation (Scholz et al. [41]). Wind braking is thought to be the dominant mechanism of rotational braking on the main-sequence and will be discussed in detail below. This sequence of events – disk braking, rapid spinup due to contraction, and onset of wind braking – is probably applicable to very low mass stars and brown dwarfs as well (Scholz & Eislöffel [44], Scholz & Eislöffel, in prep.).

Wind braking: theory vs. observations

The rotational braking due to stellar winds is usually quantified in parameterized angular momentum loss laws based on the description given by Kawaler [20], derived from wind physics by Mestel [30]: $\frac{dJ}{dt} \propto \omega^x R^{-0.5} M^{-0.5}$. We distinguish two regimes:

a) The linear regime includes all objects with $\omega < \omega_{\text{crit}}$ and is calculated with $x = 3$, reproducing the Skumanich law $J \propto t^{-0.5}$, the empirically established angular momentum loss law for solar-type main-sequence stars (Skumanich [48]).

b) The saturated regime comprises all fast rotating objects with $\omega > \omega_{\text{crit}}$ and is characterized by $x = 1$, resulting in an exponential evolution of angular momentum. To fit the observational data, $\omega_{\text{crit}}$ is normally assumed to be a function of object mass. This semi-empirical description is at the core of the most commonly used models for the rotational evolution (Krishnamurthi et al. [22], Bouvier et al. [4], Sills et al. [47], Barnes [3], Reiners & Basri [39]). For the two different regimes, I will use the
nomenclature suggested by Barnes [3]: I-sequence for the linear regime and C-sequence for the saturated regime.

In Fig. 4, a large sample of rotation periods, mostly from the Monitor program (Irwin et al. [19], [18], [17], [16]), is compared to models including disk braking at 1-5 Myr and wind braking following the approach given above. The models provide a reasonable fit to the typical period evolution for solar-mass stars from a few Myr to 4.5 Gyr. For very low masses, the models reproduce the data points for ages <500 Myr, but require a different scaling for $\omega_{\text{crit}}$ to match the periods in Praesepe. Most solar-mass stars go through a phase on the C-sequence at ages <100 Myr, before they switch to the I-sequence, causing rapid spindown. In contrast, very low mass stars stay on the C-sequence for timescales >100 Myr and thus continue to be fast rotators. As is evident from Fig. 4, there are clearly issues in reproducing the total range of periods at any given age, which can partly be resolved by taking into account core-envelope decoupling, variable disk lifetimes, and binarity.

The availability of parameterized models for the rotational evolution allows us to pursue "gyrochronology" – measuring ages of stars based on rotation rates – a method recently put forward by Barnes [2] and others. Gyrochronology relies on an accurate calibration of the spindown rates, obtained from stars with known ages. While gyro ages for solar-mass stars may already be more reliable than ages estimated from other indicators (e.g., activity, kinematic), the calibration at very low masses requires further work.

The bimodal spindown

As discussed above, the common description of the main-sequence wind braking includes a bimodal angular momentum loss law. This bimodality can be clearly seen in
observational data, particularly when rotation is plotted vs. object mass. In Fig. 5 we show periods in clusters at an age of $\sim 700$ Myr as a function of spectral type, used as a proxy for mass (Scholz & Eislöffel [40]). At this age, the objects have essentially ‘forgotten’ their pre-main sequence history, thus their rotation rates are primarily determined by wind braking.

The most obvious feature in the period-mass relation is a break at spectral types K8-M2, corresponding to masses of $\sim 0.5 M_\odot$. While late K stars are already spun down at the age of 700 Myr to periods $> 10$ d, M stars at the same age are still fast rotating with periods $< 4$ d. The figure demonstrates that the decline of the periods continues to late M spectral types. The transition from slowly rotating K dwarfs (I-sequence) to fast rotating M dwarfs (C-sequence) separates the two regimes of rotational braking. This transition is likely to be a function of mass, shifting to later spectral types as the objects become older. In $v \sin i$ data of field dwarfs it is observed at spectral types of $\sim$M3-M4 (Delfosse et al. [8], see Reiners et al., this volume).

Interpreting the transition from I- to C-sequence and the underlying physics is one of the most relevant outstanding issues in this field. As of today, we do not have a clear understanding for the breakdown of the Skumanich law at very low masses. It is tempting to explain the bimodal spindown as a consequence of the interior structure of stars: While solar-mass stars on the main-sequence have a radiative core, pre-main sequence stars and very low mass objects are fully convective. The presence of an interface layer between radiative core and convective envelope is often argued to be of prime importance for the generation of the large-scale magnetic field of the Sun (see also the contributions by Priest, Küker, this volume). The absence of a radiative core may cause a change in the magnetic field generation, the magnetic topology, and thus
the characteristics of the stellar wind.

There is indeed evidence for a change in the magnetic properties that goes along with the breakdown of the Skumanich braking at very low masses. For example, Hα activity is strongly enhanced at spectral types >M3 in field objects (Delfosse et al. [8]). Moreover, there are indications that the structure of the large-scale magnetic field (Donati et al. [9]) as well as the properties of magnetically induced spots (Scholz et al. [42]) change in the very low mass regime. Thus, the observed change in the spindown at very low masses may be one observational manifestation among others for the presence of two regimes of magnetic properties.

For further progress in this field, it is crucial to learn more about dynamo activity, magnetic field emergence, stellar winds, and how they depend on stellar age and mass. In particular, the currently used parameterized wind braking law as described above is suspect, as it has been designed and repeatedly adapted to account for observational findings, for example to match the Skumanich law and to reproduce fast rotating very low mass objects (e.g., Sills et al. [47]). Studies on how to improve the currently existing models are underway (e.g., [26]). The long-term perspective should be to replace the parameterized spindown laws by physical models, and thus describe the rotational evolution from first principles.

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