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USING ROTATION, MAGNETIC ACTIVITY AND LITHIUM TO ESTIMATE THE AGES OF LOW MASS STARS

R. D. Jeffries[1]

Abstract. The rotation rate, level of magnetic activity and surface lithium abundance are age-dependent quantities in stars of about a solar mass and below. The physical reasons for the evolution of these phenomena are qualitatively understood, but accurate quantitative models remain dependent on empirical calibration using the Sun and stars of known age, chiefly in clusters. In this work I review the status of these "empirical age indicators", outlining the astrophysics of their time dependence, describing the measurements, assessing the precision (and accuracy) of age estimates when applied to individual stars, and identifying their principle limitations in terms of the mass and age ranges over which they are useful. Finally, I discuss the "lithium depletion boundary" technique which, in contrast to the empirical methods, appears to provide robust, almost model-independent ages that are both precise and accurate, but which is only applicable to coeval groups of stars.

1 Introduction

The age of a star is, along with its mass and composition, the most important quantity to know for testing ideas concerning the evolution of stars, stellar systems (clusters and galaxies) and also, by association, their circumstellar material and exoplanetary systems. However, unlike mass and composition, we have no direct means of measuring the age of any star but the Sun. The ages of other stars are inferred or estimated using a hierarchy of techniques, which can be described as (see Soderblom 2010; Soderblom *et al.* 2013) semi-fundamental, model-dependent, empirical or statistical.

Semi-fundamental techniques rely on age-dependent phenomena where the physics is understood, there is little tuning of model parameters required and the results are basically model-independent. Model-dependent techniques include

[1] Astrophysics Group, Keele University, Keele, Staffordshire, ST5 5BG, UK
r.d.jeffries@keele.ac.uk

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isochrone fitting in the Hertzsprung-Russell (HR) diagram, asteroseismology and white dwarf cooling. Here the physics is mostly understood, but there are annoying gaps in our ability to accurately model the physics without making simplifying assumptions or tuning parameters (e.g. the mixing length) to match observations. Often the precision of the ages determined by such techniques is much better than their absolute accuracy and different models may yield ages that differ by more than their claimed uncertainties.

At a level below the model-dependent techniques are empirical age indicators. For these, the understanding of the physics is qualitative, with significant holes in the theory that are usually bridged using semi-empirical relationships with free parameters. The general approach is to calibrate an age-dependent phenomena using similar observations of stars with "known" age (the Sun and stars with ages estimated by semi-fundamental or model-dependent techniques) and then use that calibration to estimate the ages of other stars (e.g. Barnes 2007; Vican 2012). Of course, there is a risk of circularity here; one cannot study the age dependence of a phenomenon using stars with ages estimated using that phenomenon!

In this contribution I deal mainly with empirical age indicators associated with the rotation rates, levels of magnetic activity and photospheric lithium abundances of stars with masses $M \leq 1.3\,M_{\odot}$ and how they apply to stars from birth to ages of 10 Gyr. It is no coincidence that these phenomena each become useful below this mass. The presence of a sub-photospheric convection zone is responsible for dynamo-generated magnetic fields that are dissipated to provide non-radiative heating in the outer atmosphere and also couple to an ionised wind that drives angular momentum loss. The same convection zone is responsible for mixing pristine material down to interior regions where Li can be burned. The use of these indicators has its root in work done by Kraft and collaborators in the 1960s (e.g. Kraft & Wilson 1965; Kraft 1967), but perhaps the most influential early paper was by Skumanich (1972), who showed that both rotation and activity, and to some extent Li abundance, decayed according to the inverse square root of age. The data used were sparse, consisting of the Sun (age 4.57 Gyr) and a few solar-type stars in the Pleiades (age $\simeq 125$ Myr) and Hyades (age $\simeq 600$ Myr) open clusters, but nevertheless this paper stimulated much of what follows.

The utility of these empirical age indicators is mostly in estimating ages for low-mass main sequence (MS) and pre main sequence (PMS) stars that constitute the vast majority of the Galactic population. A principle advantage of the techniques I will discuss is that they are *distance independent*. With the successful launch of the *Gaia* satellite (Perryman *et al.* 2001; Brown 2008), it might seem that uncertain stellar distance will be a solved problem within a few years. However, even with precisely known distances, the determination of ages for stars that have reached the main sequence and are still burning hydrogen in their cores is difficult. Position in the HR diagram is age sensitive, but also sensitive to the detailed composition of the star. Even with [Fe/H] known to a very respectable accuracy of ± 0.05 dex, the age of a 5 Gyr solar-mass star could only be estimated to a precision of 20 per cent, and considerably worse for lower mass stars with longer main sequence lifetimes that consequently move more slowly in the HR diagram (e.g. see Fig. 20 of Epstein & Pinsonneault 2014). Asteroseismology may be an alternative distance-independent method for age estimation, with the advantage of a strong and well-understood physical basis, but it is not clear that pulsations can easily be detected in main-sequence stars well below a solar mass or in young, active stars (e.g. Huber *et al.* 2011). Even if they are, it is unlikely that ages could presently be estimated for solar-type stars to absolute precisions better than 10–15 per cent of their main sequence lifetimes (e.g. Gai *et al.* 2011; Chaplin *et al.* 2014) and would rapidly become too large to be useful in stars below a solar mass. Hence, there is likely to be a need for age determinations using empirical indicators for the forseeable future.

In section 2 I discuss measurements of rotation in low-mass stars, the physical basis on which rotation rate could be used to estimate age and review efforts to calibrate "gyrochronology". Section 3 reviews the connection between rotation and magnetic activity and the various attempts to calibrate activity-age relationships using several magnetic activity indicators. Section 4 discusses the astrophysics of lithium depletion in solar-type stars, comparison of observations and models and the use of lithium as an empirical age indicator in PMS and MS stars separately. Also included is a description of the "lithium depletion boundary" technique in very low mass stars, which differs from the other methods discussed here in that it requires no empirical calibration and is semi-fundamental. Section 5 summarises the status and range of applicability of each of these techniques and briefly discusses efforts to improve empirical calibrations. Conclusions are presented in section 6.

2 Rotation rates and gyrochronology

The motivation for using rotation rate as an empirical age indicator is discussed extensively by Barnes (2007). As well as being distance-independent it seems, at least for older stars (see below), there may be an almost unique relationship between rotation rate and age. Rotation rates are increasingly available; satellites such as *CoRoT* and *Kepler* have accumulated large quantities of rotation data (Affer *et al.* 2012; McQuillan, Mazeh& Aigrain 2014), and ground-based experiments such as *HATNet* and *SuperWASP*, aimed primarily at variability or exoplanet searches, have the potential to provide rotation periods for vast numbers of stars (e.g. Hartman *et al.* 2011; Delorme *et al.* 2011). Photometric monitoring by *Gaia* will add to this haul.

2.1 Measuring rotation rates

Rotation rates in low-mass stars can be found in a number of ways (see the review by Bouvier 2013), but only two are mentioned here; the others are generally more difficult to apply routinely. Spectroscopy can be used to estimate that component of spectral line broadening contributed by rotation – the projected equatorial velocity, $v\sin i$. This can be accomplished by a direct Fourier transform of the spectrum (e.g. Gray 1976; Dravins, Lindegren & Torkelsson 1990) and with very high quality data, it can even be feasible to measure differential rotation with latitude (e.g. Reiners 2007). More frequently, $v \sin i$ is estimated by calibrating the width of a cross-correlation peak against template stars or synthetic spectra with similar atmospheric parameters (e.g. Rhode, Herbst & Mathieu 2001). Although feasible using a single spectrum, and in the case of cross-correlation, a spectrum with very modest signal-to-noise ratio, the principle limitations of spectroscopic methods are the high resolving powers and accurate characterisation of the intrinsic (non-rotating) line profiles required to estimate $v \sin i$ for slow rotators, and the confusing $\sin i$ axis orientation term.

The main alternative, and method of choice, is to monitor the brightness of stars and detect periodic modulation caused by dark magnetic starspots or bright chromospheric plages on their surfaces. Magnetic activity is required for this technique to work, so is best suited to low-mass stars at younger ages with vigorous rotational dynamos (see section 3), where typical modulation amplitudes can be a few mmag to tenths of a magnitude. Typical examples of such studies can be found in Prosser *et al.* (1993), Allain *et al.* (1996), Herbst *et al.* (2000) and Irwin *et al.* (2009), which also demonstrate a progression in the efficiency of monitoring facilitated by the advent of large format CCDs. The principle advantage of this technique is that many stars can be almost simultaneously monitored using telescopes of modest aperture (compared with those required for spectroscopy). The disadvantages are that stars need to be monitored intensively and over at least a couple of rotation periods. There is also a potential bias towards the young, most active and most rapidly rotating stars – even in young, magnetically active cluster populations ≤ 50 per cent of stars have measured rotation periods and older stars may have such small photometric amplitudes and long periods that only space-based photometry is good enough. Both the *Kepler* and *CoRoT* satellites have provided much more precise, lengthy time-series data for field stars (and some clusters) to partly nullify these problems (e.g. Meibom *et al.* 2011a; Affer *et al.* 2012; Reinhold, Reiners & Basri 2013; McQuillan *et al.* 2014).

Prior to *Kepler* and *CoRoT*, most information about the rotation of older, less active stars came from chromospheric inhomogeneities monitored in the Ca II H and K lines (e.g. Donahue, Saar & Baliunas 1996; Baliunas *et al.* 1996), because the contrast between chromospheric plages and the immaculate photosphere is greater than for starspots in stars as old/inactive as the Sun. Monitoring on decadal timescales at the Mount Wilson observatory has yielded many rotation periods for solar-type field stars as well as quantitative measurements of their magnetic activity and magnetic activity cycles (see section 3).

2.2 Rotational evolution and models

2.2.1 Observed rotational evolution

Most progress in understanding the rotational evolution of solar-type and lower-mass stars comes from observations of rotation rates (predominantly rotation periods) in clusters of stars, whose members are assumed coeval and of similar com-

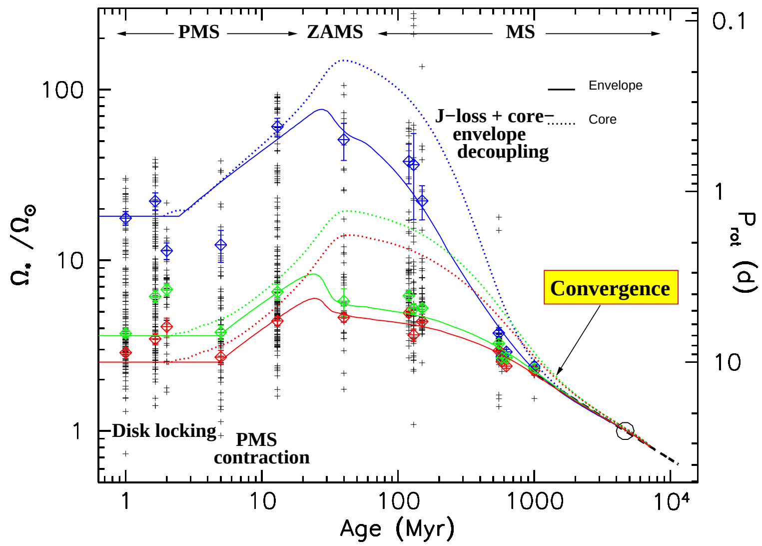

Fig. 1. Rotation rates/periods for sets of solar-type stars in coeval clusters as a function of age (adapted from Gallet & Bouvier 2013). The PMS, ZAMS and MS phases are marked and the dominant physical processes at work are indicated. Beyond ages of ~ 0.5 Gyr rotation rates converge for stars of a solar mass, or at least are predicted to converge, to a close-to-unique function of age. This convergence takes longer at lower masses.

position. Compilations of data and reviews of the observations can be found in Irwin & Bouvier (2009), Gallet & Bouvier (2013) and Bouvier *et al.* (2013), and these sources also provide an overview of theoretical interpretations of these observations. Figure 1 (from Gallet & Bouvier 2013) illustrates the main features of rotational evolution for groups of stars at around a solar mass, ranging in age from star forming regions at a few Myr, through to the ZAMS at ~ 100 Myr and onto later main sequence life beyond a Gyr.

Solar-type stars evidently begin their lives with a wide range of rotation periods between about 1 and 15 days (e.g. in the Orion Nebula cluster; Herbst *et al.* 2002, or NGC 2264; Makidon *et al.* 2004). Over the first 10 Myr of their lives this distribution changes little despite the order of magnitude reduction in moment of inertia as stars contract along their PMS tracks. Interactions between the star and its circumstellar disk are invoked to remove angular momentum, a process that ceases upon the dispersal of inner disks on timescales of a few Myr. This idea finds support from the correlation found in some star forming regions between the presence of disks/accretion and slower rotation (e.g. Edwards *et al.* 1993; Rebull *et al.* 2006; Cieza & Baliber 2007).

The rotation rate distributions in older clusters show gradual evolution towards faster rotation rates at the ZAMS, presumably as a result of PMS contraction. Although the long-period envelope remains fairly constant in solar-type stars, there are few slow rotators among lower mass ($\leq 0.5\,M_{\odot}$) stars at ages of 10-200 Myr, with most having rotation period $P < 3\,$d (e.g. Irwin *et al.* 2007, 2008). The range of rotation rates in solar-type stars rapidly increases to nearly two orders of magnitude; at $\sim 15\,$Myr the rotation rate distribution is still quite flat but the range has grown to $0.2 < P < 15\,$days (e.g in the h Per cluster; Moraux *et al.* 2013). At $\sim 50 - 150$ Myr the bulk of solar-type ZAMS stars have $6 < P < 10\,$days, but a tail of rapid rotators persists to periods as short as 0.3 days (e.g. in the Alpha Per and Pleiades clusters; Prosser *et al.* 1993; Krishnamurthi *et al.* 1998; Hartman *et al.* 2010).

Beyond the ZAMS, with the moment of intertia essentially fixed, the wide distribution of rotation rates in solar-type stars converges, a process thought to be driven by a magnetised stellar wind, with angular momentum losses that increase with rotation rate. Convergence is almost complete for solar-type stars at ages of $\geq 500\,$Myr (e.g. in the Hyades; Radick *et al.* 1987, or in M37; Hartman *et al.* 2009). The timescale for convergence is however mass-dependent and fast rotating K-dwarfs are still seen in clusters with ages of a few hundred Myr (e.g. in M34; Meibom *et al.* 2011b), whilst M-dwarfs with rotation periods $< 1\,$d are still observed in the Hyades and Praesepe clusters at ages of $\sim 600\,$Myr (Delorme *et al.* 2011; Agüeros *et al.* 2011). In fact if anything, the dispersion in rotation rates appears to grow with age in these lower-mass stars as evidenced in the wide range of periods found for (predominantly old) field M dwarfs (Irwin *et al.* 2011; McQuillan, Aigrain & Mazeh 2013).

2.2.2 Rotational evolution models

Models to interpret these data are semi-empirical; there are several components that, whilst physically motivated, require calibration using cluster data and the current rotation rate of the Sun. Starting from an initial rotation period at a very young age, the effect of torques and moment of inertia changes are followed and models include some or all of the following ingredients:

Star-disk interactions: There is no general agreement yet on which mechanisms prevent the spin-up of contracting PMS stars, but the presence of an inner disk appears to be implicated. The necessary transfer of angular momentum may be provided via the original "disk-locking" proposed between the accretion disk and stellar magnetic field (Camenzind 1990; Koenigl 1991); more recent ideas include accretion-driven winds or magnetospheric ejections (e.g. Matt & Pudritz 2005; Zanni & Ferreira 2013). Whatever is responsible, most rotational evolution models assume that rotation rates are held constant until the inner disk disperses. This disk dispersal timescale, observationally found to be in the range 1–10 Myr, almost certainly varies from star-to-star for poorly understood reasons and is a tuneable model parameter, largely set by the difference in the mean and range of rotation rates at the ZAMS compared with those in the initial distribution (e.g. Bouvier, Forestini & Allain 1997).

PMS Contraction: Once disks disperse then stars are free to spin-up if they have not reached the ZAMS. The moment of inertia will decrease roughly on the Kelvin-Helmholtz timescale – around 10 Myr for a solar mass star, but hundreds of Myr for lower-mass stars (i.e. much longer than any disk dispersal timescale). Stellar (surface) spin up is moderated both by angular momentum losses and the possible decoupling of radiative core and convective envelope (see below).
Wind angular momentum loss: The large scale magnetic B-field of a star will force its ionised stellar wind into co-rotation out to some distance approximated by the Alfven radius. Upon decoupling, the wind carries away angular momentum at a rate that depends on the rotation rate of the star, the mass-loss rate, the strength and geometry of the magnetic field and the details of the wind velocity profile and interaction with the magnetic field (Mestel & Spruit 1987). A common parametrisation attributable to Kawaler (1988) and Chaboyer, Demarque & Pinsonneault (1995a) is

$$\frac{dJ}{dt} = f_k K_w \left(\frac{R}{R_\odot}\right)^{2-N} \left(\frac{M}{M_\odot}\right)^{-N/3} \left(\frac{\dot{M}}{10^{-14}}\right)^{1-2N/3} \Omega^{1+4N/3} \quad (\Omega < \Omega_{\rm crit})\,, \tag{2.1}$$

$$\frac{dJ}{dt} = f_k K_w \left(\frac{R}{R_\odot}\right)^{2-N} \left(\frac{M}{M_\odot}\right)^{-N/3} \left(\frac{\dot{M}}{10^{-14}}\right)^{1-2N/3} \Omega\,\Omega_{\rm crit}^{4N/3} \quad (\Omega \geq \Omega_{\rm crit})\,, \tag{2.2}$$

where N is an index specifying the B-field geometry ($N = 2$ is radial, $N = 3/7$ represents a dipolar field), $\dot{M}$ is the wind mass-loss rate in solar masses per year, K_w is a constant ($= 2.036 \times 10^{33}$ in cgs units), f_k is a parameter that encapsulates the constant of proportionality in an assumed linear relationship between surface magnetic *flux* and rotation rate Ω, as well as uncertainties in the wind speed as it decouples from the field at the Alfven radius. The strong dependence on Ω is the main physics behind the convergence of rotation rates in later main sequence life. $\Omega_{\rm crit}$ is a threshold rotation rate at which the B-field and consequently the angular momentum loss rate "saturate". This is motivated by the need to ensure that fast-rotating stars do not spin-down too quickly upon reaching their ZAMS radius and the observation that saturation is observed in chromospheric and coronal indicators of magnetic activity (see section 3).

Of these parameters, several need to be assumed (e.g. N, the relationship between B-field and rotation rate) or fixed by ensuring that at 4.5 Gyr, the rotation rate of the Sun is reproduced (e.g. f_k). If $N \simeq 1$ the angular momentum loss rate is not too dependent on the assumed $\dot{M}$, which is fortunate as there are few constraints on this for stars younger than the Sun. Some of these degrees of freedom are beginning to be constrained by new MHD simulations, albeit still with simplifying assumptions about B-field geometry (e.g. Matt *et al.* 2012). Using equation 2.1 for a star with a fixed moment of inertia and $\Omega < \Omega_{\rm crit}$ leads directly to $\Omega \propto t^{-\alpha}$, with $\alpha = 1/2$, as suggested by Skumanich (1972). However, it is of critical importance in what follows to note that the $t^{-1/2}$ behaviour is very dependent on model assumptions and is by no means assured of applying at all masses. For instance Reiners & Mohanty (2012) have pointed out that if there is instead a linear relationship between magnetic *field* and rotation rate then the radius dependence of dJ/dt is much stronger (e.g. $\propto R^{16/3}$ for a radial field rather than radius-independent in equation 2.1). As R changes even during main sequence evolution, this changes the form of $\Omega(t)$. Similarly, any mass-dependent or time-dependent changes in $\dot{M}$ or B-field topology will alter α and possibly give it a mass- or time-dependence.

Core-envelope decoupling: As angular momentum is lost from the surface, interior processes act to transport angular momentum within stellar radiative zones - these may include hydrodynamic instabilities, magnetic fields or gravity waves (Mestel & Weiss 1987; Chaboyer *et al.* 1995a; Pinsonneault 1997; Mathis *et al.* 2013; Mathis 2013; Charbonnel *et al.* 2013). Some studies treat this numerically as a diffusion process within radiative zones Denissenkov *et al.* 2010; Eggenberger *et al.* 2012), others allow the radiative core and convective envelope to rotate as solid bodies at different rates with a coupling timescale (e.g. MacGregor & Brenner 1991; Gallet & Bouvier 2013). In either case there are free parameters associated with the diffusion coefficients or coupling timescales that can partly be constrained by what we know about the internal rotation of the Sun and also its surface lithium abundance (see section 4), but otherwise must be considered free parameters that may depend on mass or surface rotation rate.

2.2.3 Putting it together

Parametrised models incorporating some or all of these features have been studied by many authors in the past decades; more recent studies include Denissenkov *et al.* (2010), Spada *et al.* (2011) and Gallet & Bouvier (2013). Models begin with an assumed rotation rate for young stars and typically assume this rotation rate is constant whilst the star possesses an inner disk. A prescription for wind angular momentum losses and a stellar evolution model are then used to follow rotation rate as the star contracts and loses angular momentum. The core and envelope may be treated as separate solid body rotators with a coupling timescale. There are sufficient free or assumed parameters in this model (e.g. the dynamo prescription, initial rotation rate, disk lifetime, coupling timescale, f_k, $\Omega_{\rm crit}$) that reasonable fits can be found to the observed distribution of rotation rates. Another degree of freedom is the mass-dependence of these parameters. It has been known for some time that models which match the evolution of rotation rate distributions for solar-type stars do not adequately match those of lower mass stars using the same set of parameters (e.g. Sills, Pinsonneault & Terndrup 2000; Irwin *et al.* 2011). A mass-dependent $\Omega_{\rm crit}$, changes in magnetic topology or dynamo location, or wind braking laws with a more extreme mass/radius dependence (e.g. Reiners & Mohanty 2012; Brown 2014) may provide solutions, but at the moment we are some way from being able to directly estimate stellar ages from models of rotational evolution.

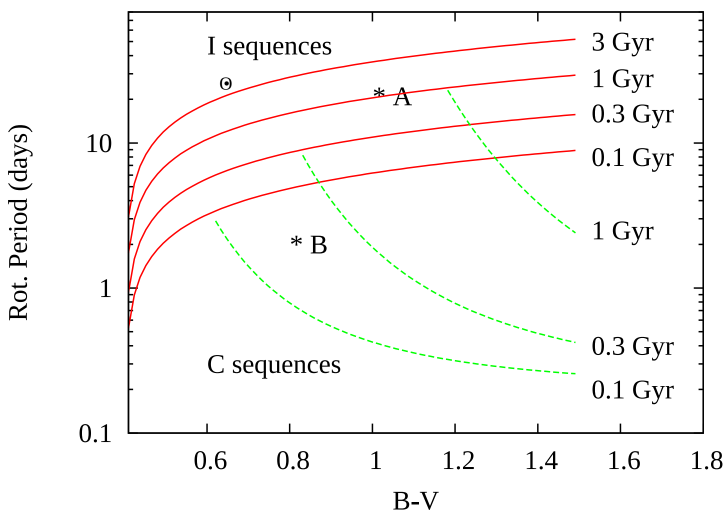

Fig. 2. A schematic of the location of the I- and C-sequences in the rotation period, colour plane. The I-sequences (gyrochrones) were calculated according to the formula advocated by Barnes (2007), the C-sequences from the formula given by Barnes (2003). The Sun and two illustrative stars (A and B) are shown and discussed in the text.

2.3 Empirical gyrochronology

2.3.1 Gyrochrone construction and use

The observed evolution of rotation rate distributions and a semi-empirical understanding of the processes involved offer both problems and opportunities. The broad range of rotation rates seen in solar-type stars between about 1 and 200 Myr, and to even older ages for lower mass stars, mean that rotation rate is a *poor* age indicator for individual stars at these ages. However, the model predictions of a convergence in rotation rates to a single-valued function of age for older main sequence stars, and observations that suggest this may actually happen at least to ages of a Gyr or so in solar-type stars, suggest that rotation *can* be a good empirical age indicator for these stars.

Barnes (2003, 2007) noted that when plotted in the P versus $B-V$ plane, stars in young (<1 Gyr) clusters and older field stars appear to populate two distinct sequences (schematically illustrated in Fig. 2) and which Barnes termed the I- and C-sequences. The I-sequence appears well-established in a number of clusters and is formed from those stars with converged rotation rates, roughly following the $\Omega \propto t^{-1/2}$ Skumanich law. The C-sequence appears less tight and is populated by rapidly rotating stars, which are in the saturated regime of magnetic activity (see section 3.2) with $\Omega > \Omega_{\rm crit}$. As the convergence timescales are observed to be longer in low-mass stars, the junction of these two sequences moves redward, with everything blueward of the junction being on the I-sequence. Barnes suggested that stars on the I-sequence have a fully (magnetically) coupled core and envelope, whereas in stars on the C-sequence the core and envelope are decoupled. The dearth of objects between the two sequences reflects a short evolutionary timescale between the two states and Barnes (2003) interpreted this as a switching between a convective (C) and an interface (I) dynamo that couples the core and envelope, causing a rapid spindown.

Irrespective of the (strongly debated – e.g. Denissenkov *et al.* 2010; Barnes & Kim 2010; Brown 2014) physical processes at play, the phenomenon of an I-sequence can be used to estimate stellar ages. The basic procedure is to say that rotation rate is a *separable* function of both age and colour/mass/$T_{\rm eff}$. i.e.

$$P(B-V,t) = f(B-V)\,g(t)\,, \tag{2.3}$$

$$f(B-V) = a\,[(B-V)-b\,]^{c}\,, \quad \text{and} \quad g(t) = t^{\alpha}\,. \tag{2.4}$$

The function f is chosen to match the shape of the I-sequence in young clusters, whilst $\alpha = 0.5$ is equivalent to the Skumanich spin-down law. A number of authors have calibrated relationships of this type (e.g. see Table 1 in Epstein & Pinsonneault 2014); f is found from fitting one (or several) clusters in the P vs $B-V$ plane, whilst α is determined by matching the solar rotation rate. Different authors find α in the range 0.52–0.57 and there are significant differences in the form of f too (Barnes 2007; Mamajek & Hillenbrand 2008; Meibom, Mathieu & Stassun 2009, 2011a; Collier Cameron *et al.* 2009).

Figure 2 shows gyrochrones (I-sequences) calculated from equations 2.3 and 2.4, with the parameters derived by Barnes (2007), and C-sequences generated according to the functional form defined by Barnes (2003). Two hypothetical stars, A and B, are shown along with the Sun. Star A lies just above the 1 Gyr I-sequence gyrochrone *and* to the left of the C-/I-sequence junction for 1 Gyr. Therefore its age can be estimated as just greater than 1 Gyr. Star B however lies well below the 0.1 Gyr I-sequence but *to the right* of the 0.1 Gyr C-sequence. As stars with ages up to about 0.3 Gyr could exist at this period/colour (on or above their C-sequences) then about the best we can say as that star B is < 0.3 Gyr. This is a fundamental limit of gyrochronology that traces back to the large scatter in rotation rates seen at ages prior to the (mass-dependent) convergence.

2.3.2 Problems, precision and accuracy

In addition to the fundamental problem at young ages just discussed, it can be difficult to measure the rotation period of a star. Whilst young stars (or those with short periods) *may* have a healthy photometric modulation amplitude that can be detected from the ground (actually censuses of rotation period are often < 50 per cent complete even in young clusters), this is not generally true at older ages, where precision photometry from space is required (see Fig.9 in Reinhold, Reiners & Basri 2013). Alternatively, chromospheric modulation can be used in older stars (e.g. Donahue *et al.* 1996), but is *much* more expensive in terms of observing time. The precision and accuracy of gyrochronology may also be affected by measurement uncertainties, differential rotation, limited convergence, binarity and most importantly, calibration uncertainties.

Differential rotation: The precision of most period measurements is high, but stars may have differential rotation with latitude such that the period measured at one epoch may not be that measured at another, depending on the latitudinal starspot distribution. Differential rotation has been studied using the Mt Wilson chromospheric activity time-series, finding $\Delta P/P \simeq 0.05\,P^{0.3}$ (Donahue *et al.* 1996; where ΔP is the range of periods found at a single epoch). Reinhold *et al.* (2013) use Kepler data to show that, compared with the Sun (which has $\Delta P/P \sim 0.14$) differential rotation increases with $T_{\rm eff}$ and P. If $\Delta P/P = 0.1$ and $P \propto t^{-1/2}$, then this leads to an age uncertainty of 20 per cent if only a single measurement of P is available.

Limited convergence: The assumption of convergence to a unique I-sequence is approximate. Convergence takes longer at lower masses and so the older and more massive the star, the better this approximation is. Epstein & Pinsonneault (2014) perform simulations and show that this dominates over likely uncertainties caused by differential rotation at $M < 0.7\,M_{\odot}$ and grows very rapidly below $0.4\,M_{\odot}$. Conveniently, convergence becomes a problem in stars where differential rotation is unlikely to be important and vice-versa, so the overall precision of gyrochronology is likely abut 20 per cent in most cases. The situation may be a little better in stars with ages of 0.5–1 Gyr. The empirical scatter of rotation periods around the I-sequence in such clusters suggest that the combination of differential rotation and incomplete convergence could lead to age errors of only 9–15 per cent (Collier Cameron *et al.* 2009; Delorme *et al.* 2011).

Binarity: Most of the discussion in this section applies to single stars or at least stars that are effectively isolated from their companions as far as angular momentum transfer is concerned. In particular, stars in close, tidally locked binary systems may appear to rotate at rates much faster than in a single star of similar age.

Calibration uncertainties: Gyrochronology is essentially calibrated using a group of young ($\leq$ 600 Myr) clusters and the Sun. In particular, the assumptions of separable mass and time dependencies and a simple, unique power-law time dependence may not be true. For example different wind angular momentum loss prescriptions give quite different predictions of the mass-dependence of Ω, even when tuned to match the rotation rate of the Sun (Reiners & Mohanty 2012). In addition, mass or time-dependencies in $\dot{M}$, B-field topology and stellar radius could lead to radically different gyrochrone shapes and spacing at lower masses and older ages. Some confidence can be gained by noting that the gyrochronological ages of the components of a few (wide) binary pairs with known rotation periods and differing masses are roughly in agreement (Barnes 2007), but they have large individual uncertainties and there are indications that these ages may not agree with those from asteroseismology (Epstein & Pinsonneault 2014). There is an urgent need for better calibrating data (stars with known age and rotation period) at lower masses than the Sun and at ages of 1-10 Gyr (see section 5.2).

3 Magnetic activity as an age indicator

3.1 Magnetic activity indicators

Some of the difficulties associated with calibrating gyrochronology can be addressed by using proxies for rotation that are easier to measure. In stars with outer convection zones it appears that a rotational dynamo can sustain a magnetic field, which emerges from the photosphere and provides a source of non-radiative heating, leading to the formation of a chromosphere and a hot corona.

Indicators of magnetic activity include coronal X-ray emission from gas at 10^6–10^7 K. The chromosphere is at lower temperatures but there are many emission lines that can be found which act as diagnostics of the magnetic heating process(es), found mainly in the blue and ultra-violet part of the spectrum, but which also include Balmer-line emission. Each of these diagnostics demands different technologies and techniques for their study and describing these is beyond the scope of this review. Here we just need to know that usually, a *distance-independent* magnetic activity index can be formed from the excess emission beyond that expected from a normal photosphere, normalised by the bolometric luminosity. The principal examples in most of the literature on age determination are: the Mt Wilson $R'_{\rm HK}$ index, formed from the chromospheric flux found in the cores of the Ca II H and K lines normalised by the bolometric flux; and the ratio of X-ray to bolometric flux.

Generally speaking, magnetic activity indices are easier to measure than a rotation period and are often assessed with a single epoch of observation – though this can bring problems (see below). There are of course limitations imposed by the sensitivity of instruments, the distance to the stars in question and the contrast between the photosphere and the magnetic activity indicator, which gets weaker as stars become less active. i.e. Just like rotation, activity gets harder to measure in older stars.

3.2 The rotation-activity relationship

The utility of magnetic activity as an age indicator arises because of its close connection with rotation. This connection, ultimately due to the nature of the interior dynamo that amplifies the magnetic field, has been empirically understood for some time. For instance Pallavicini *et al.* (1981) noted a good correlation between X-ray luminosity and the square of the rotation velocity; Noyes *et al.* (1984) found an equivalent inverse correlation between flux in the Ca II H and K lines and the rotation period. Noyes *et al.* also noted that a much tighter correlation could be found between the ratio of chromospheric flux to bolometric flux ($R'_{\rm HK}$) and the inverse of the Rossby number (N_R, the ratio of rotation period to turnover time at the base of the convection zone). The turnover time increases with decreasing mass and N_R has become the parameter of choice in activity-rotation correlations because it reduces the scatter when combining data for stars with a range of masses and convective turnover times (e.g. Dobson & Radick 1989; Pizzolato *et al.* 2003; Jeffries *et al.* 2011; Wright *et al.* 2011).

At small N_R (shorter rotation periods, or longer convective turnover times at lower masses or in PMS stars) X-ray and chromospheric activity indicators *saturate*. They reach a plateau at $N_R \leq 0.1$ below which they do not increase further, whilst at larger N_R, activity decreases (Vilhu & Walter 1987; Pizzolato *et al.* 2003). $N_R = 0.1$ corresponds to $P \simeq 3\,\mathrm{d}$ for a solar type star, but $P \simeq 6\,\mathrm{d}$ for an M0 star with a longer turnover time. This saturation poses serious difficulties for the use of activity as an age indicator in young stars. The period at which saturation occurs in solar mass stars is just below the I-sequence gyrochrone at 100 Myr, so a large fraction of stars at this age and younger have saturated magnetic activity and therefore the observation of saturated magnetic activity in a star can only yield an upper limit to its age. This age ambiguity grows at lower masses because the increasing convective turnover times and longer spin-down timescales of lower mass stars means that a larger fraction of stars are saturated at a given age and they remain in the saturated regime for longer.

3.3 Empirical activity-age relationships

3.3.1 X-ray activity

Reviews of what is empirically known about the time-dependence of magnetic activity can be found in Randich (2000), Ribas *et al.* (2005) and Güdel (2007). Figure 3 shows an empirical relationship between X-ray luminosity and age for stars of about a solar mass. Different symbols show mean levels and the interquartile range from surveys of open clusters with "known age" (data are from Randich 2000; Flaccomio, Micela & Sciortino 2003; Preibisch & Feigelson 2005, and references therein) and data for a few field stars and the Sun, where ages have been estimated by other means, and where lines connect multiple measurements of the same star (Telleschi *et al.* 2005; Güdel 2007). These data are not complete, but they illustrate the basic principles and problems of using empirical activity-age relations to estimate ages.

The overall decay of X-ray activity with age is clearly seen, but the decay is not rapid for the first few hunded Myr, especially if the X-ray luminosities were normalised by bolometric luminosity to make them distance independent age indicators. In addition there is scatter at all ages that cannot be attributed to observational uncertainties. In the very young clusters there is at least an order of magnitude range of L_x (or $L_x/L_{\rm bol}$). This spread is not associated with rotation; most stars here have very low Rossby numbers that would put them in the saturated regime. Some of the spread may be associated with flaring or the presence of circumstellar material (e.g. Wolk *et al.* 2005; Flaccomio, Micela & Sciortino 2012). In the young ZAMS clusters the spread in X-ray activity remains, but this is known *not* to be due to variability (e.g. Simon & Patten 1998; Jeffries *et al.* 2006) and these stars have lost their circumstellar material . Instead,

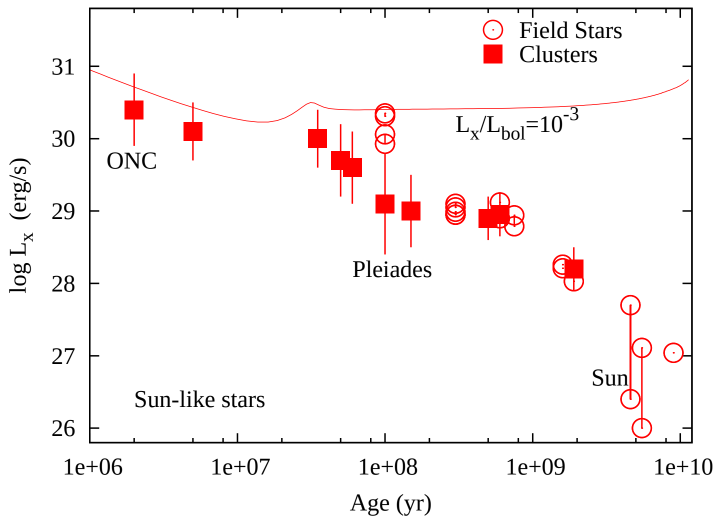

Fig. 3. The age-dependence of coronal X-ray luminosity for stars of about a solar mass. The median L_x for clusters are shown with squares; the error bars indicate the interquartile range. Open circles are measurements of field stars with estimated ages. Lines connect observations of the same star at different epochs. The solid line indicates the locus where $L_x/L_{\rm bol} = 10^{-3}$ (from the models of Siess, Dufour & Forestini 2000), which is the observed saturation threshold for X-ray activity.

the rotation-activity correlation is at work. Many stars have spun down below the threshold where their activity is saturated and hence exhibit lower activity levels, whilst other stars in the same cluster remain as rapid rotators. The lack of variability and strong connection with rotation persists until at least the Hyades at an age of 600 Myr, with $L_x/L_{\rm bol}$ being proportional to $N_R^{-2.7}$ in the unsaturated regime (Wright *et al.* 2011).

Beyond 1 Gyr we expect from Fig. 1 that rotational convergence has taken place, $\Omega \propto t^{-1/2}$, and hence $L_x/L_{\rm bol} \propto t^{-1.35}$. If anything, the decay looks like it may be a little steeper than this but there are no old open clusters with good ages near enough to study in detail with X-ray telescopes. Ribas *et al.* (2005) derived a time-dependence of between $t^{-1.27}$ and $t^{-1.92}$ for the soft and hard X-ray fluxes from 6 solar analogues in the field. Observations of field stars reveal, in contrast to the younger stars, a high level of variability on timescales of years. The Sun's soft X-ray emission changes by almost two orders of magnitude on a roughly 11-year cycle (Strong & Saba 2009) and there are now observations of several solar analogues that indicate that at some point beyond 1 Gyr, large (order of magnitude) and possibly cyclic variability of X-ray emission may commonly occur (e.g. Favata *et al.* 2008; Robrade *et al.* 2012).

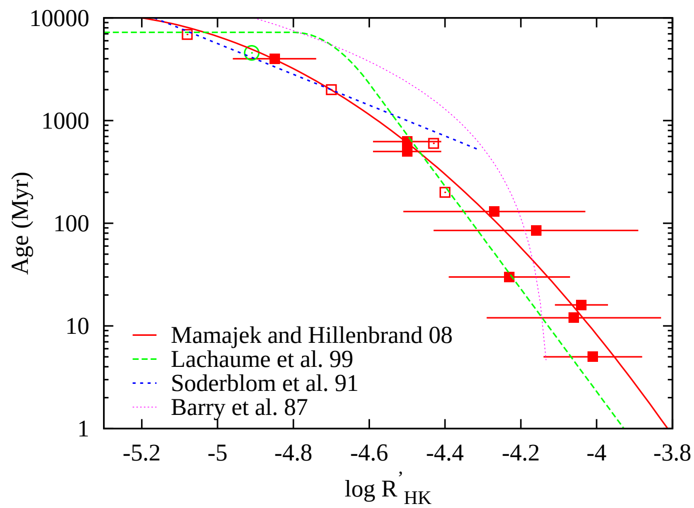

Fig. 4. The age-dependence of the chromospheric $R'_{\rm HK}$ index. The data are taken from Mamajek & Hillenbrand (2008). Solid points are clusters with HK measurements on the Mt Wilson system. The horizontal bars represent the rms dispersion. Open symbols are several clusters with data recalibrated onto the Mt Wilson system (see Mamajek & Hillenbrand for details); the Sun is also shown. Various age-activity relations proposed in the literature are shown. The Mamajek & Hillenbrand curve was defined using the plotted data. Note the large dispersion in $R'_{\rm HK}$ at ages ≤ 200 Myr, presumably caused by a large spread in rotation rates.

In terms of mass dependence, the decay of coronal activity closely follows what happens with rotation rates. Lower mass stars take longer to spin down and remain in the saturated regime for longer. So, whilst X-ray activity is a poor age indicator for the first 100 Myr in a solar-type star, this period extends to 1 Gyr or more in M-dwarfs. The longer spin down timescales also mean that field M-dwarfs tend to be more active than field G-dwarfs (when expressed as $L_x/L_{\rm bol}$, e.g. Preibisch & Feigelson 2005).

Even once stars have spun down and reached the converged I-sequence of rotation periods, X-ray activity is still not a very good age indicator because of the high levels of variability. This limits precisions to about a factor of two in age. In principle this could be improved by monitoring the activity of a star over many years, but this is not usually practical. Instead, the recent focus of activity-age relations has turned to chromospheric emission in the form of the $R'_{\rm HK}$ index.

3.3.2 Chromospheric activity

In general as one considers activity indicators that arise from lower/cooler layers in the magnetically heated outer atmosphere, the time dependence becomes less steep ($\sim t^{-1/2}$, e.g. Skumanich 1972; Ribas *et al.* 2005; Findeisen, Hillenbrand & Soderblom 2011) and this appears to be true for G-, K- and M-dwarfs (Stelzer *et al.* 2013). This is because of the rather steep slope in the correlation between chromospheric and coronal activity indicators (e.g. $L_X/L_{\rm bol} \propto (R'_{\rm HK})^{3.46}$; Mamajek & Hillenbrand 2008). However, typical levels of variability in the $R'_{\rm HK}$ index for stars that are young or old are only 5–10 per cent (Baliunas *et al.* 1995), though young stars are still of course affected by a spread in rotation rates and saturation of chromospheric emission. So, even after taking account of the shallower $R'_{\rm HK}$-age relation, we see that chromospheric activity ages should suffer less than coronal activity ages from uncertainties due to magnetic activity cycles and other variability in older stars.

There are several flavours of $R'_{\rm HK}$-age relations in the literature (e.g. Barry, Cromwell & Hege 1987; Soderblom, Duncan & Johnson 1991; Lachaume *et al.* 1999), which are reviewed in some detail by Mamajek & Hillenbrand (2008), who then provide an updated calibration (see Fig. 4) and also provide a $L_x/L_{\rm bol}$-age relationship that is bootstrapped from the chromospheric calibration. The $R'_{\rm HK}$-age relation suffers less than the $L_x/L_{\rm bol}$-age relation from problems with variability at older ages as discussed above, but the limitations associated with spreads in rotation rate and hence activity at younger ages are just as severe. A further key advantage of the $R'_{\rm HK}$-age relation is that there are good data for solar-type stars in the old open clusters M67 and some data in NGC 188. These calibration "points", consisting of a set of coeval stars at 4 and 6.9 Gyr, give an excellent estimate of the precision of the method. Further tests are provided by the comparison of chromospheric ages for stars in wide binary systems, with either similar components or components with different masses.

3.4 Problems, precision and accuracy

Mamajek & Hillenbrand (2008) conclude that for solar-type stars older than a few hundred Myr, carefully measured $R'_{\rm HK}$ values yield log age to ± 0.2 dex, or an age precision of ~ 60 per cent. The uncertainty grows rapidly at younger ages, due to the growing dispersion in $R'_{\rm HK}$ (see Fig. 4), to become unusable at ≤ 100 Myr except in providing an upper limit to the age of a star. For reasons that are not clear (perhaps binaries have smaller amplitude activity cycles?), the dispersion in empirically determined age between the components of binary systems is lower than the dispersion implied by the spread of observed chromospheric activity in the presumably coeval stars of the Hyades and M67.

A further limitation of the chromospheric activity-age relation is that calibrating data for lower mass stars is more sparse. Attempts to determine the slope of the $R'_{\rm HK}$-mass (or colour) relation from cluster data yield a wide diversity of results. Instead, Mamajek & Hillenbrand (2008) use a newly derived activity-N_R

relation and combine this with a gyrochronology relation to create an activity-age-colour relationship, calibrated for F7-K2 main sequence stars. This assumes that stars have converged to the I-sequence and also makes the same assumptions about the separable nature of the colour and time dependence of rotation rate used in other gyrochronology relations. The new relation does reduce the dispersion in ages estimated for the binary components with different masses, but the dispersion estimated for stars in M67 remains stubbornly at the ± 0.2 dex level. The situation is similar for X-ray activity indicators, though likely to be worse at older ages despite a steeper decline with age, because coronal X-ray variability is much greater than that of the chromosphere in older stars.

Further limitations to the technique mirror those discussed for gyrochronology in section 2.3.2. Whilst differential rotation should not be a problem, the limited convergence of rotation rates onto the I-sequence may be partly responsible for the dispersion in ages estimated for coeval stars. Like gyrochronology, activity-age relationships should not be used for close binary systems where tidal or other interactions may have affected the rotation rates of the components. Finally, like gyrochronology, the activity-age relationships (both coronal and chromospheric) are poorly calibrated at ages older than, and masses lower than, the Sun. Attempts to improve this situation are briefly reviewed in section 5.2.

4 Lithium depletion and age

The "ecology" of lithium in the universe makes it a fascinating probe of many physical processes, ranging from the big-bang to cosmic ray spallation reactions and mixing in stellar interiors. ^{7}Li is produced during the first minutes of a standard big-bang (Wagoner, Fowler & Hoyle 1967) at a predicted abundance (post-*Planck*) of ^{7}Li/H$= 4.89^{+0.41}_{-0.39} \times 10^{-10}$, or A(Li)$= 2.69^{+0.03}_{-0.04}$, on a logarithmic scale where A(H)$= 12$ (Coc, Uzan & Vangioni 2013). This abundance is significantly higher than seen in old population II stars, which exhibit a plateau of Li abundance versus $T_{\rm eff}$ at A(Li)$= 2.20 \pm 0.09$ (Sbordone *et al.* 2010) – the "Spite plateau" (Spite & Spite 1982). This discrepancy suggests either "new" physics beyond the standard big-bang model or that physical processes have been able to deplete Li from the photospheres of these old stars.

On the other hand, the abundance of Li found in meteorites is A(Li)$= 3.26 \pm 0.05$ (Asplund *et al.* 2009), which implies that the interstellar medium in the Galaxy becomes Li-enriched with time. Several production mechanisms are under investigation; inside AGB stars, cosmic ray spallation, novae (Prantzos 2012). The photospheric solar ^{7}Li abundance is A(Li)$= 1.05 \pm 0.10$ and observations of solar-type stars in the field and open clusters reveal a wide dispersion of A(Li), from less than the solar value to approximately the meteoritic abundance, clearly indicating that depletion mechanisms are at work. It is the time-dependence of these depletion processes that makes Li abundance a potential age indicator.

4.1 Lithium in pre main sequence stars

4.1.1 The astrophysics of PMS Li depletion

After PMS stars are born, they initially contract along fully-convective Hayashi tracks. Once their cores reach temperatures of $\sim 3 \times 10^6$ K, then Li burning commences through the reaction[1] ^{7}Li(p,^{4}He)^{4}He. The reaction is extremely temperature dependent ($\sim T^{20}$; Bildsten *et al.* 1997), the density dependence is secondary. Li-depleted material at the core is convectively mixed upwards and replaced with fresh material and the star could then be completely depleted of Li on a timescale of a few–10 Myr (much less than the Kelvin-Helmholtz contraction timescale).

In stars with $M < 0.4\,M_{\odot}$, that remain fully convective right through to the ZAMS, this is indeed what happens. However, higher mass stars develop a central radiative core because their central opacity falls far enough to reduce the temperature gradient below the critical value necessary to trigger convection. Convective mixing to the core ceases and the extent to which *photospheric* Li depletion will continue depends now on the temperature of the convection zone base ($T_{\rm BCZ}$). In stars of $M \leq 0.6 M_{\odot}$ (based on the models of Siess, Dufour & Forestini 2000), $T_{\rm BCZ}$ remains above the Li-burning threshold long enough to completely deplete Li in the photosphere, but in more massive stars Li-depletion should eventually be halted as the radiative core expands. If $M > 1.1\,M_{\odot}$ the radiative core forms before Li-depletion commences and such stars deplete very little Li. $T_{\rm BCZ}$ is never hot enough to allow Li-burning in stars with $M \geq 1.3\,M_{\odot}$ and their photospheric Li should remain at its initial value.

It is worth emphasizing that the above discussion takes account only of convective mixing of material and predicts that depletion of photospheric Li should have ceased by ~ 100 Myr in all stars with $M \geq 0.4\,M_{\odot}$ and considerably earlier in stars of higher mass; i.e. the pattern of Li depletion versus mass should be settled prior to arrival on the ZAMS. Many flavours of evolutionary model have made predictions about the onset and rate of photospheric Li depletion and these can be used to define isochrones of Li depletion in the A(Li) versus $T_{\rm eff}$ plane (see Fig. 5).

For stars that develop a radiative core, the predicted Li depletion as a function of $T_{\rm eff}$ is highly sensitive to the physics included in the models – the opacities (and therefore metallicity), the efficiency of convection parametrised in terms of a mixing length or overshooting, and the adopted atmospheres (e.g. Chaboyer, Pinsonneault & Demarque 1995b; Piau & Turck-Chièze 2002). For instance, at $T_{\rm eff} \simeq 5000$ K, the models of Baraffe *et al.* (2002) with mixing lengths of 1.0 pressure scale height or 1.9 pressure scale heights (the value that matches the solar luminosity at the solar age) have depleted Li by factors of 0.6 and 0.06 respectively at an age of 125 Myr (see Fig. 5).

[1]The isotope ^{6}Li is burned at lower temperatures and should be completely depleted in all the stars discussed here.

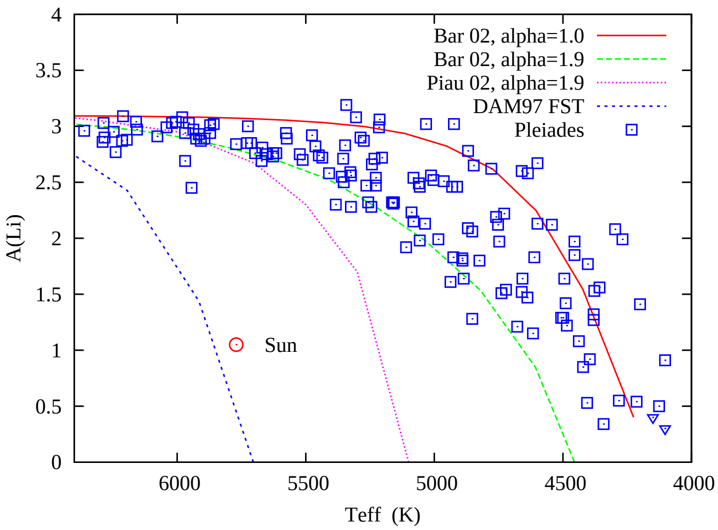

Fig. 5. Lithium abundances measured in the Pleiades (age 125 Myr) at the end of PMS Li depletion (Soderblom et al. 1993; Jones *et al.* 1996). The lines are isochrones of Li depletion at 125 Myr predicted by various models (D'Antona & Mazzitelli 1997; Baraffe *et al.* 2002; Piau & Turck-Chièze 2002).

4.1.2 Models vs observations

Lithium is almost always measured using the resonance doublet of Li I at 6708Å. There are other transitions in the optical spectrum at 6104Å and 8126Å, but these are *much* weaker and blended with stronger lines. Even in cool stars Li is almost completely ionised, the line strengths are temperature sensitive (in warmer stars) and subject to NLTE effects that perturb abundances by up to 0.3 dex depending on the Li abundance, $T_{\rm eff}$ and metallicity of the atmosphere (e.g. Carlsson *et al.* 1994). Basic curves of growth for the Li I 6708Å feature have been calculated by a number of authors (e.g. Soderblom *et al.* 1993; Palla *et al.* 2007). These show that at A(Li)~ 3, the equivalent width (EW) is about 0.5Å and in the saturated part of the curve of growth in cool stars ($T_{\rm eff} < 3500\,K$), while it is weaker (~ 0.15Å), but more sensitive to abundance, in solar type stars. The 6708Å line is also blended with a Fe I line at 6707.44Å. This is much weaker than the Li feature for stars with undepleted Li but a more accurate assessment of this blend becomes important as Li is depleted (Soderblom *et al.* 1993). Other problems associated with estimating an accurate Li abundance arise from an accurate estimation of $T_{\rm eff}$, especially in young, active stars with spots and chromospheres, and photospheric veiling by an accretion continuum may need to be accounted for in PMS stars with disks.

A further problem in comparing models with observations is that models predict Li *depletion*, so an initial abundance must be adopted. For most young clusters this is usually assumed to be close to the solar meteoritic value; there is also evidence from very young (assumed to be undepleted) T-Tauri stars that $A(\mathrm{Li})_{\mathrm{init}} \simeq 3.1$–$3.4$ (e.g. Martín *et al.* 1994; Soderblom *et al.* 1999). There are however plausible reasons from Galactic chemical evolution models and some observational evidence that the initial Li may be positively correlated with [Fe/H] (e.g. Ryan *et al.* 2001; Cummings *et al.* 2012). It seems reasonable to assume that for young stars near the Sun there could be a ± 0.1–0.2 dex spread in the initial A(Li).

Figure 5 represents the most basic comparison of PMS Li depletion with models, showing Li abundances in the Pleiades, which has an age of 125 Myr (Stauffer, Schulz & Kirkpatrick 1998), versus a number of representative model isochrones (at $\simeq 100$ Myr) from the literature (D'Antona & Mazzitelli 1997; Piau & Turck-Chièze 2002; Baraffe *et al.* 2002). The solar photospheric Li abundance is also shown. This Figure illustrates several important points:

- There appears to be little Li depletion (assuming an initial A(Li)= 3.2) among G-stars and this is predicted by most of the models. As the scatter in abundance ($\simeq 0.2$ dex) is similar to the amount of depletion in G-stars and similar to the uncertainty in initial Li abundance, Li depletion will not be an accurate age indicator below 125 Myr for these stars.

- The models differ vastly in their predictions of PMS Li depletion in cooler stars. There are several differences between these models, but the dominant one as far as Li depletion is concerned is convective efficiency.

- Models that have a convective efficiency (mixing length) tuned to match the Sun's luminosity (the Piau & Turck-Chièze 2002 model and the Baraffe *et al.* 2002 models with mixing length set to 1.9 pressure scale heights) predict too much Li depletion. A lower convective efficiency provides a better match (see also Tognelli, Degl'Innocenti & Prada Moroni 2012).

- A scatter in Li abundance develops in this coeval cluster at $T_{\mathrm{eff}} < 5500$ K that cannot be accounted for by observational uncertainties (~ 0.1–0.2 dex) or explained by the models shown.

The large disagreements between the various model flavours and the failure of these models to match the Pleiades or to predict the scatter among the K-stars means that Li abundance in solar-type stars (those that develop a radiative core) cannot yet be used as anything but an *empirical* age indicator. However, the scatter at a given T_{eff} (or colour) is a problem in that regard too, since stars of similar age may show a wide dispersion in their Li abundances. Unless the factors causing this dispersion can be identified, there is an inevitable uncertainty on any age inferred from an Li abundance.

There is a long list of possible causes of the Li-abundance dispersion that have been considered. It seems possible that some fraction of it may be caused by atmospheric inhomogeneities or chromospheric heating of the upper photosphere (e.g. Randich 2001; King *et al.* 2010), but it is unlikely to be dominant given the

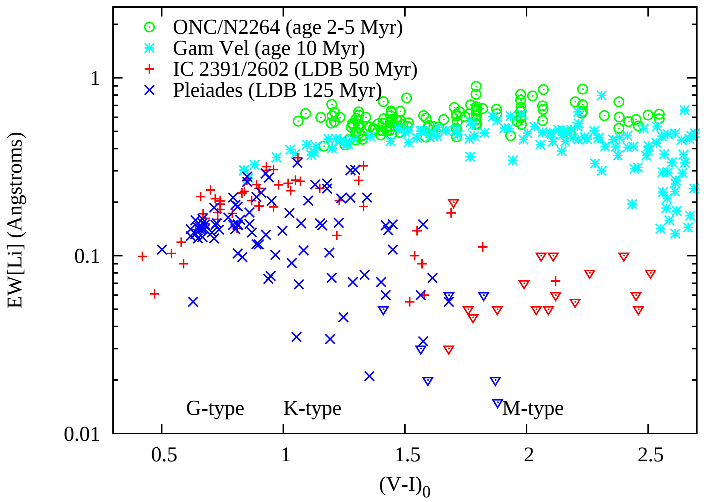

Fig. 6. Empirical Li depletion patterns for a set of fiducial clusters in the form of equivalent width of the 6708Å features vs (dereddened) colour. Data are from Soderblom *et al.* (1993); Jones *et al.* (1996); Randich *et al.* (1997, 2001); Sergison *et al.* (2013); Jeffries *et al.* (2014).

lack of variability in the line strengths (Jeffries 1999) and the agreement between abundances derived from the 6104Å and 6708Å features. A big clue may be the correlation with rotation, noted for the Pleiades by Soderblom et al. (1993) and García López, Rebolo & Martín (1994), and now seen in several other young clusters (though not always so strongly e.g. IC 2602, Alpha Per and several young kinematic groups – Randich *et al.* 2001; da Silva *et al.* 2009; Balachandran, Mallik & Lambert 2011), in the sense that fast rotators (usually only projected rotation velocity is available) have preserved more Li. It is unlikely that the structural effects of rotation have much influence, so attention has focused on additional rotational mixing of Li, which may be greater in slower rotators with more internal differential rotation (see Fig. 1 and Bouvier 2008; Eggenberger *et al.* 2012), or the inhibition of convective mixing by stronger magnetic fields in rapid rotators (e.g. D'Antona, Ventura & Mazzitelli 2000; Somers & Pinsonneault 2014).

A further problem with using Li as an empirical age indicator in young stars is that PMS Li depletion is predicted to be very sensitive to metallicity. For example, the models of Piau & Turck-Chièze (2002) show an order of magnitude increase in ZAMS Li depletion for a solar mass star if the metallicity is increased by just 0.1 dex. The effect is smaller at a fixed $T_{\rm eff}$ (about 0.2 dex in Li depletion per 0.1 dex change in [M/H] at $T_{\rm eff} \simeq 5700\,$K – Somers & Pinsonneault 2014), but grows towards cooler stars. Fortunately, although puzzlingly for theoreticians, this extreme metallicity dependence is not observed. Pairs of clusters with similar ages but differing metallicities have only minor differences in Li depletion pattern, and pairs of clusters with similar metallicities but different ages have Li depletion patterns ordered by age (e.g. Jeffries *et al.* 2002). It is possible that the metallicity dependence is mostly masked by the time-dependence of processes that either inhibit or enhance PMS Li depletion (see Somers & Pinsonneault 2014). Hence an accurate knowledge of a *young* star's metallicity does not greatly increase the precision with which an age can be inferred from Li depletion.

Figure 6 shows how Li can be used to infer ages in the form of a plot of Li I 6708Å EWs versus colour (in the absence of differential reddening, it is preferable to show the data in the untransformed observational plane, rather than Li abundance versus $T_{\rm eff}$) for a number of clusters with ages found by more certain methods (e.g. see section 4.3). Li is empirically sensitive to age within a mass and age range where Li depletion has begun, but Li is still detectable in the photosphere. If Li is undepleted then only an upper limit to an age is possible, whilst if all the Li has gone then an age lower limit is implied. For isolated stars this means that Li can be used to estimate ages between about 10 and 50 Myr for M-dwarfs and between about 20 and a few 100 Myr in K-dwarfs (Li has disappeared in K-dwarfs by 600 Myr in the Hyades – Soderblom *et al.* 1995). The dispersion at a given age, limits precision to about a factor of two. G-dwarfs deplete little Li on the PMS, and as this depletion is comparable to uncertainties in initial Li, then Li depletion cannot be confidently used to estimate ages in the range shown.

As a result of the above discussion, Li has mainly been used in the literature for *identifying* young stars in circumstances where their ages are otherwise uncertain (e.g. they cannot be placed on an HR diagram because their distances are unknown). A boundary can be defined in Fig. 6, such that a star with an EW(Li) above the boundary is younger than some desired threshold. Examples include finding low-mass members of star forming regions, especially weak-lined T-Tauri stars with no obvious accretion or circumstellar material (Alcala *et al.* 1996; Martin 1997 and many more since), or identifying members of spatially dispersed members of young, kinematic groups (e.g. Jeffries 1995; Zuckerman & Webb 2000; Montes *et al.* 2001). Little effort has so far been applied to obtaining quantitative age estimates (or age probability distributions) for individual stars, though attempts have been made to put groups of coeval young stars in age order using Li (e.g. Mentuch *et al.* 2008). One notable problem in this endeavour is a lack of well-populated calibrating clusters between ages of 10 and 50 Myr.

4.2 Lithium in main sequence stars

Figure 5 shows that the Sun has depleted Li by ~ 2 dex compared with similar mass stars at the ZAMS in the Pleiades. Such depletion is entirely unanticipated by "standard" models that include only convective mixing and is also observed in field stars at a range of $T_{\rm eff}$ around the solar value. Additional mixing mechanisms have been proposed that will mix Li-depleted material from the hot radiative core to the base of the convection zone and hence to the photosphere. These include atomic diffusion (Richer & Michaud 1993) or mixing induced by hydrodynamcal instabilities associated with rotation or gravity waves (e.g. Vauclair 1988; García López & Spruit 1991; Pinsonneault 1997, 2010; Charbonnel & Talon 2005). At present, models of age-dependent Li depletion that incorporate these effects have significant uncertainties, including the usually unknown rotational history of the star, and require tuning to match the solar Li abundance and solar interior rotation profile derived from helioseismology. Furthermore, these extra mixing mechanisms act in addition to standard PMS Li depletion, but we have already seen that standard models predict too much Li depletion in ZAMS clusters and fail to predict the significant dispersion that is observed. Such uncertainties merely prevent us from confidently inferring the age of a star by comparing its Li abundance to a model. Indeed, the primary use of Li abundance data for older stars and clusters has been to attempt to shed light on these uncertain interior processes. However, the option is still open to empirically calibrate Li depletion beyond the ZAMS using clusters, the Sun and other stars of "known" age.

4.2.1 Li in field stars

General surveys of Li abundances in field stars (e.g. Lambert & Reddy 2004; Takeda & Kawonomoto 2005; Ramírez *et al.* 2012) show a strong temperature dependence − Li is depleted by $\geq 3\,$dex or gone in all stars with $T_{\rm eff} < 5200\,K$, whilst stars at the solar $T_{\rm eff}$ show a $\sim 2\,$dex dispersion, with the Sun towards the bottom of the distribution. At higher temperatures the dispersion may narrow again, though there are still some F-stars with very low abundances. It is worth mentioning that measuring the Li abundance in older stars is more challenging, because the EW of the Li I 6708Å feature becomes only a few mÅ at A(Li)$\simeq 1$ in solar-type stars.

Naturally, one would like to know to what extent this scatter is due to age (at a given $T_{\rm eff}$) and how much is due to confounding (but potentially resolvable) parameters like metallicity (higher opacities lead to a deeper convection zone, more PMS Li depletion and more effective MS mixing) or even the presence of planets (Bouvier 2008; Israelian *et al.* 2009), and how much might be due to factors that are more difficult to take into account. For example, the rotational history of the star, which appears to affect PMS depletion and is predicted to be a strong influence on MS Li depletion, is not easily determined once rotational convergence has been reached ($\geq 500\,$Myr for solar-type stars).

There is considerable debate on these points in the literature. Baumann *et al.* (2010) determine ages from HR diagrams (with typical uncertainties of $\simeq \pm 1.5\,$Gyr) for solar analogues and find that there is the expected correlation with age for stars in a tight $\pm 0.1\,$dex [Fe/H] range around the solar value. There is still a A(Li) scatter of $\sim 1\,$dex at a given age, but they attribute this to spreads in the initial rotation conditions of these stars (and find no evidence that the presence of exoplanets is relevant). The larger sample of Ramírez *et al.* (2012) also demonstrates that stars with $M < 1.1\,M_{\odot}$ have greater Li depletion with age and increasing metallicity (and again it is found that exoplanet hosts do not deplete more Li than similar stars with no detected planets), but with a large scatter around the correlations. On the other hand, for a small sample of stars with metallicity and mass very close to the solar value, Monroe *et al.* (2013) claim an extremely tight correlation between Li depletion and age, with essentially no scatter. The Sun's Li abundance lies on this correlation and Monroe *et al.* suggest that previous studies, suggesting a large scatter in this relationship and that the solar A(Li) was low, either had insufficient spectral quality or encompassed too wide a range of metallicity and mass to eliminate the dispersion caused by these factors. This latter study, which needs confirmation with a larger sample, holds out the promise of a deterministic relation between A(Li) and age if the mass and metallicity can be accurately determined. However, it makes no reference to Li observations in older clusters, which appear to tell a different story.

4.2.2 Li in older post-ZAMS clusters

The progress of post-ZAMS Li depletion can be empirically followed in the Li depletion patterns of older clusters. Samples in clusters should be coeval (if membership can be established!) and have the added advantage that a good mean metallicity can often be determined from the analysis of a number of stellar spectra. Initial studies included the Hyades and Praesepe at ages of about 600 Myr (e.g. Wallerstein, Herbig & Conti 1963; Boesgaard & Tripicco 1986; Boesgaard & Budge 1988; Soderblom *et al.* 1990), NGC 752 (age 1.7 Gyr, Hobbs & Pilachowski 1986a) and M67 (age 4 Gyr, Hobbs & Pilachowski 1986b). These studies, which were focused on stars at the solar $T_{\rm eff}$ and hotter, immediately revealed what has been termed the "F-star Li gap". Stars in a narrow range $6400 < T_{\rm eff} < 6800$ K can deplete their Li to undetectable limits (A(Li)< 1.8) by the age of the Hyades, a process that appears to have begun at ages of ~ 150 Myr (Steinhauer & Deliyannis 2004). The cause of the "Li gap" is still not fully understood, but likely involves rotation-driven mixing (Deliyannis *et al.* 1998). In principle, if $T_{\rm eff}$ can be precisely measured, then the Li abundance in this temperature range could strongly constrain the stellar age between 150 Myr and ~ 600 Myr.

Older stars of late F-type and cooler are fainter and harder to study in distant clusters. Sestito & Randich (2005) provide a review of the important literature and a homogeneous reanalysis of the Li abundances. Randich (2010) reviews subsequent observations, mostly made with the 8-m VLT. These observations of solar-type stars in ~ 10 clusters with ages between 600 Myr and 8 Gyr paint a confusing picture. There is little scatter in the A(Li) vs $T_{\rm eff}$ relationship in the Hyades and this seems to be true in some older clusters like Be 32 and NGC 188 at ages of 6–8 Gyr, but solar-type stars in these clusters have 10–20 times as much lithium as the Sun (Randich, Sestito & Pallavicini 2003). On the other hand there are also examples of old clusters (e.g. M67, NGC 6253) where there is a large dispersion in A(Li), with some stars that are as depleted as the Sun, but others with A(Li)$\simeq 2.3$ (e.g. Pasquini *et al.* 1997, 2008).

It appears that the Li in solar-type stars is slowly depleted (by a factor of 3–4) from about the age of the Pleiades to 1 Gyr. In this range it seems reasonable to use Li as an age indicator – the dispersion in A(Li) among clusters in this interval suggests an age precision of only about 0.3 dex though. Beyond 1 Gyr some stars appear to deplete Li further whilst others do not. It is unclear at present what factors drive this dichotomy. If a star has a very low abundance then it clearly indicates an age > 2 Gyr, but if A(Li)~ 2 then the constraint can only be that the age is ≥ 500 Myr.

4.3 The lithium depletion boundary

In stars that remain fully convective all the way to the ZAMS ($M < 0.4\,M_{\odot}$) then Li burning will completely deplete Li from the entire star. Core Li burning begins at an age which depends upon the mass and hence luminosity of the PMS star. Li depletion occurs quickly, so that in a group of coeval stars there should be a sharp boundary between stars exhibiting complete Li depletion and stars with only slightly lower luminosities that still retain all their initial Li (Bildsten *et al.* 1997). This "lithium depletion boundary" (LDB) was first used to confirm the identity of brown dwarf candidates in the Pleiades – substellar objects should have retained their Li in the Pleiades, but older, more massive objects with similar spectral types would have depleted Li (Basri, Marcy & Graham 1996; Rebolo *et al.* 1996). Since then, the LDB technique has been used to estimate the ages of 10 clusters and associations by finding the luminosity (or absolute magnitude) of the faintest star which has significantly depleted its Li.

The LDB method, as defined above, is almost independent of which evolutionary models are used. The luminosity of the LDB is insensitive to changes in the assumed convective efficiency, composition, atmosphere and equation of state. Burke, Pinsonneault & Sills (2004) performed a set of tests using different input physics finding systematic uncertainties in the range 3–8 per cent. It is worth noting though that ages might be perturbed due to some factor that is assumed or ignored by all models. An example could be extensive coverage by starspots; the blocking of flux at the photosphere would inflate the star leading to a lower central temperature and an underestimated LDB age (e.g. Jackson & Jeffries 2014; Somers & Pinsonneault 2014).

The relationship between the luminosity of the LDB and age is steep ($L_{\rm LDB} \propto t^{-2}$ at $20 < t < 100$ Myr. As a result, typical errors of 0.1 mag in distance moduli or bolometric corrections, lead to 10 per cent uncertainty in $L_{\rm LDB}$ and hence only 5 per cent age uncertainties. Locating the LDB in relatively sparse datasets is usually more of an issue, and the presence of unresolved binary systems, which may appears 0.75 mag brighter than a single star of the same type, can be a confusing factor (e.g. Jeffries & Oliveira 2005).

The LDB method is only applicable to groups of stars in clusters (see Table 1 in Soderblom *et al.* 2013), but has also been applied to spatially dispersed members of young kinematic groups (the Beta Pic group with an LDB age of 21 ± 4 Myr, Binks & Jeffries 2014; the Tuc-Hor group with an LDB age of 41 ± 2 Myr, Kraus *et al.* 2014). In isolated very low-mass stars, the presence of undepleted Li at a given luminosity can give an upper limit to the age, whilst if a star has depleted all its

Li then a lower limit to the age is implied. Note that the above discussion refers only to the *luminosity* at the LDB, which of course depends on a distance. The temperature or spectral type at the LDB could be used as a distance-independent marker, but unfortunately the model-insensitivity of the $L_{\rm LDB}$-age is not reproduced and the $T_{\rm LDB}$-age relation is quite shallow. Hence such determinations are of much lower precision and subject to significant model-dependent uncertainties dominated by which atmospheres are used and the adopted convective efficiency in the models. A further limitation of the LDB technique is that below 20 Myr there is an increasing dispersion in model predictions and below 10 Myr some evolutionary models predict no Li depletion at any mass. At older ages the $L_{\rm LDB}$-age relation becomes much shallower and no Li depletion is expected in objects with $M < 0.065\,M_{\odot}$. However, the principal limitation is telescope size. Objects around the LDB at ages ≥ 200 Myr are so intrinsically faint that the $R \geq 3000$ spectroscopy needed to measure the Li I 6708Å feature is impractical, even with 8-m telescopes.

Although the measurement of an LDB age is limited to only a few clusters, the fact that the derived ages are mostly model-independent means that they can be used to test or calibrate other age estimation techniques at 20–200 Myr in the same clusters (actually the oldest LDB age so far reported is for Blanco 1 at 132 ± 24 Myr; Cargile, James & Jeffries 2010). So far, systematic comparisons have only been carried out between LDB ages and ages determined by fitting the positions of high-mass stars in the HR diagram (see Soderblom *et al.* 2013). Such comparisons reveal that high-mass models without "convective core overshoot" yield ages that are 50 per cent lower than the LDB ages in some clusters (e.g. the Pleiades and Alpha Per clusters; Stauffer *et al.* 1998, 1999), implying that moderate core overshooting or fast rotation in the high mass stars (or some combination of the two) is required. Similar systematic comparison with empirical age indicators, such as those discussed here, are likely to be valuable additions that can improve the *accuracy* of the empirical ages.

5 The status of rotation, activity and lithium depletion as age indicators

In this section I summarise the status of each of the considered age indicators and point to ongoing developments that might improve the precision and especially the accuracy of these ages. This review was written from the point of view of estimating the ages of individual stars in the field, which is likely to remain the most important application – e.g. estimating the ages of exoplanet hosts (Walkowicz & Basri 2013) or searching for spatially dispersed members of kinematic groups (e.g. Shkolnik, Liu & Reid 2009; da Silva *et al.* 2009). New data from the *Gaia* satellite and large spectroscopic surveys such as the *Gaia-ESO survey* (Gilmore *et al.* 2012) will add impetus to this field, with the desire to understand stellar ages and hence the chemical and dynamical history of our Galaxy. All of the techniques discussed have limitations when applied to isolated stars, caused by star-to-star dispersions in the empirical relationships. Of course, if many (assumed) coeval stars are available, then this dispersion can be overcome to give a mean age estimate for the group. I have not emphasized this application because usually in such cases there are age determination methods that are higher up in the accuracy hierarchy (e.g. fitting cluster sequences in an HR diagram, see section 1). However in the case of kinematic groups where the distances to individual members may not be well known, then the *distance-independence* of these empirical relationships may be of benefit (e.g. Mentuch *et al.* 2008).

5.1 Applicability of the techniques

Figure 7 summarises in a schematic way where each technique can feasibly yield an age (or a limit to the age) as a function of age and mass.

5.1.1 Rotation and gyrochronology

Rotational evolution is not fully understood, however it appears that magnetised winds act to cause the convergence of an initially wide spread of rotation rates on a timescale of $\sim 100\,\mathrm{Myr}$ for G-type stars, but as long as $1\,\mathrm{Gyr}$ for stars of $0.5\,M_{\odot}$, accounting for the steeply sloped lower boundary in Fig. 7a. Prior to this convergence, stars have a dispersion in rotation rate and only age upper limits can be determined. Once convergence is achieved (or nearly achieved), then ages can be estimated with a precision of ± 20 per cent. The precision is determined in younger stars by the remaining dispersion in rotation rates at a given age, and in older stars by differential rotation with latitude. The precision will be much poorer in stars with $M \leq 0.4\,M_{\odot}$, where convergence is likely to be incomplete even at very old ages.

The dark shaded region of Fig. 7a indicates that region where gyrochronology is well-calibrated using young clusters ($\leq 1\,\mathrm{Gyr}$) and the Sun. The lighter shaded region indicates where gyrochronology could work in principle, but where calibrating data are absent and so the accuracy of the technique may be poor when using calibrations extrapolated from younger and hotter stars.

5.1.2 Magnetic activity

As magnetic activity depends on rotation, then unsurprisingly, its region of applicability, shown in Fig. 7b, is similar to that of gyrochronology. The lower boundary is determined by the large spread of activity levels seen in young stars as a result of their varied rotation rates. The lower boundary has a shallower slope than in Fig. 7a because at $0.5 < M/M_{\odot} < 1$ there should be a small mass range at a given age, just below the mass at which rotational convergence occurs, but where the *maximum* rotation rate leads to activity lower than the saturated activity level and hence an age could be estimated. However at very low masses, the rapid increase in convective turnover time leads to stars at a wide range of ages having rotation rates fast enough to cause saturated activity.

Activity diagnostics are generally easier to measure than rotation periods, especially in older stars and so the well-calibrated region for the activity-age relation-

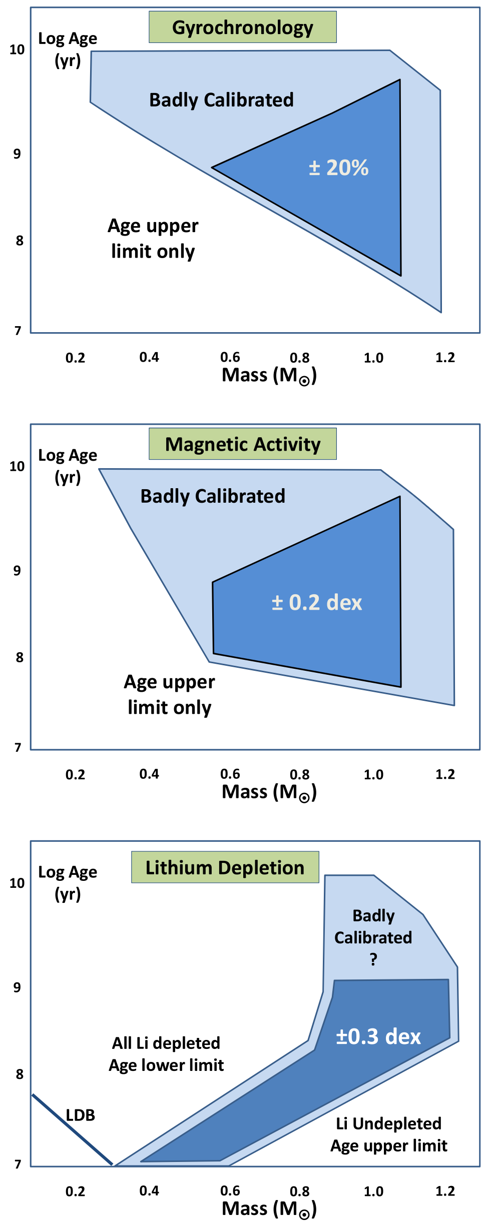

Fig. 7. Schematic diagrams illustrating the range of ages and masses where each empirical technique can be used to estimate ages or upper limits for individual stars.

ship is larger than for gyrochronology, with $R'_{\rm HK}$ data for a couple of older clusters providing more confidence in the calibration around a solar mass. Nevertheless, these relationships are poorly constrained at lower masses and the precision is roughly three times worse than gyrochronology in mature stars. This is likely due to magnetic activity cycles, so in principle could be mitigated by repeated observation on long timescales.

5.1.3 Lithium depletion

Lithium abundances can only yield an age in the range where Li is *being* depleted. If the Li has gone, then a lower limit to the age can be inferred; if Li is undepleted, only an upper limit can be determined. The shape of the applicability region shown in Fig. 7c is a function of the mass-dependent timescale for PMS Li depletion for stars with $M < 1\,M_{\odot}$ and the observed timescale of main-sequence depletion in older solar-type stars. Precision is unlikely to be better than a factor of two until it is fully understood why there is a dispersion of Li abundance in stars of the same $T_{\rm eff}$ and age in calibrating clusters.

Beyond 1 Gyr, both the theoretical and observational pictures are confused. There appears to be a wide range of possible Li abundances for stars like the Sun. This may be connected with their rotational history, the presence of planets or some other factor; but for now it seems that Li abundance cannot be used to estimate ages in older stars.

At the low mass side of Fig. 7c, the narrow stripe represents (schematically) the lithum depletion boundary (LDB). Fully convective low-mass stars deplete their Li very rapidly (in a few Myr). Thus in individual stars it would normally only be possible to provide a one-sided limit on the stellar age. However, the power of the LDB is that in a coeval group of stars with a range of masses, the transition across this diagonal boundary will take place at an age-dependent mass or luminosity, allowing the age of the ensemble to be determined accurately.

5.2 Ongoing efforts to improve calibrations

For all three of the discussed empirical methods there is a need for more calibration to improve the *accuracy* of the ages and assess their precision. On the gyrochronological front, determining rotation periods in stars of known age and at lower masses requires (a) relatively nearby old clusters that still have a low-mass population, despite the ongoing processes of energy equipartition, mass segregation and tidal stripping, or other samples of stars with "known" ages; (b) space-based observations because spot modulation amplitudes in older stars are very small. Meibom *et al.* (2011a) discuss results for NGC 6811, one of 4 clusters between 0.5 and 9 Gyr that are present in the Kepler field. NGC 6811 has an age of 1 Gyr and a population spanning F- to early K-types. Of more interest will be the results for NGC 6819 (2.5 Gyr) and NGC 6791 (9 Gyr), though their low-mass populations may be very sparse.

It is also worth noting that the clusters M35, Praesepe, the Hyades and the

Pleiades are possible targets for the Kepler K2 mission during 2014/15 (Howell *et al.* 2014). Whilst these clusters are not old, the data should constrain much better the degree of rotational convergence between 125 Myr and 600 Myr, providing a much more complete census of rotation periods, especially in the low-mass populations.

It is also possible to use Kepler data to provide asteroseismological ages for many of the brighter (and predominantly solar-type) stars in the Kepler field. Asteroseismology can give ages to perhaps 10–15 per cent in these stars and they can then be used to calibrate rotation-age, activity-age and Li-age relationships. This work has already begun: Karoff *et al.* (2013) found $P = f(B-V)\, t^{0.81\pm0.10}$ for a small group of solar-type stars with asteroseismological ages and a Skumanich-like decay in chromospheric activity. From the Sun and a small sample of stars with $0.9 < M/M_{\odot} < 1.2$ and ages from 1–9 Gyr, Garćia *et al.* (2014) determine a relationship $P \propto t^{0.52\pm0.09}$, in much closer accord with earlier work (see section 2.3.1).

Other approaches to fix the ages of possible calibrating stars include using objects which are in resolved binary systems with either subgiants, giants or white dwarfs. The HR diagram (or white dwarf cooling model) is a much more precise tool for estimating the companion age in these cases so, providing there is no possibility of previous interaction or exchange of angular momentum, then the main sequence companion could be used as a calibrator of empirical age indicators. Examples include Silvestri *et al.* (2006), Chanamé & Ramírez (2012), Rebassa-Mansergas *et al.* (2013) and Bochanski *et al.* (2013). No clear results have yet emerged from these programs in terms of calibrating the activity-age or rotation-age relationships.

6 Summary

The need for empirical methods of age estimation in low-mass stars is likely to be present for some years to come. In this contribution I have reviewed the astrophysical reasons that rotation, magnetic activity and the photospheric abundance of lithium, change with time in low-mass stars ($\leq 1.3\, M_{\odot}$). Whilst theoretical models that predict these behaviours are improving rapidly, there are still very significant uncertainties and semi-empirical components that prevent their use in directly estimating stellar ages with any certainty, and which require calibration using stars of known age. Each of these empirical age indicators can play a role in various domains of mass and age, that are schematically illustrated in Fig. 7. The rotation-age relationship (or gyrochronology) offers the best prospect of determining precise (to 20 per cent) ages in older stars, and could be complemented by the use of PMS Li depletion to estimate the ages of younger stars at low masses. Magnetic activity offers a less precise age determination in older stars, but is usually easier to measure than rotation. In terms of accuracy, all these methods are compromised to some extent by a lack of calibrating data in stars that are older than the Sun or of lower masses than the Sun.

In very low mass stars, the sharp transition between stars that have depleted all their lithium and stars with similar age but only slightly lower luminosities that have preserved all their lithium (the lithium depletion boundary), offers an almost model-independent way of estimating an age for groups of coeval stars. This technique is sensitive between ages of 20 and 200 Myr and can be used to investigate the uncertain physics in stellar models or calibrate empirical age indicators.

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