Rotation, inflation, and lithium in the Pleiades

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ABSTRACT

The rapidly rotating cool dwarfs of the Pleiades are rich in lithium relative to their slowly rotating counterparts. Motivated by observations of inflated radii in young, active stars, and by calculations showing that radius inflation inhibits pre-main sequence (pre-MS) Li destruction, we test whether this pattern could arise from a connection between stellar rotation rate and radius inflation on the pre-MS. We demonstrate that pre-MS radius inflation can efficiently suppress lithium destruction by rotationally induced mixing, and that the net effect of inflating and rotational mixing is a pattern where rotation correlates with lithium abundance for $M_\star < M_\odot$, and anti-correlates with lithium abundance for $M_\star > M_\odot$, similar to the empirical trend in the Pleiades. Next, we adopt different prescriptions for the dependence of inflation on rotation, and compare their predictions to the Pleiades lithium/rotation pattern. A connection between rotation and radius inflation naturally and generically reproduces the important qualitative features of this pattern. This is the first consistent physical model to date that explains the Li-rotation correlation in the Pleiades. We discuss plausible mechanisms for inducing this correlation, show that our results are insensitive to assumptions about angular momentum transport, and suggest an observational test using granulation.

1 INTRODUCTION

The classic Vogt–Russell theorem states that the mass and composition of a star uniquely determines its structure in hydrostatic equilibrium. Although this paradigm has proven to be a strong overall guide during the main sequence (MS), the implicit assumptions in the Vogt–Russell theorem break down in the pre-MS, where substantial star-to-star variations in luminosity are ubiquitous at fixed $T_{\text{eff}}$ in star forming regions (e.g. Hillenbrand 1997). This behaviour has traditionally been interpreted as the signature of an intracluster age spread, but an alternative explanation is that stars at fixed mass and age can have non-uniform stellar parameters (i.e. radius) induced by processes neglected in traditional models, such as rotation, mass accretion, and magnetic fields. Much attention has been paid to understanding these processes, as a complete picture of pre-MS evolution is crucial for inferring the ages of young star forming regions, measuring the low end of the stellar initial mass function, and constraining the distribution of circum-stellar disc lifetimes, which in turn have important implications for both the angular momentum evolution of stars and the formation of planets.

The light element $^7$Li is a sensitive diagnostic of proto-stellar structure. Lithium burns through the $^7$Li($p$, $\alpha$)$^4$He reaction at a temperature $T_{\text{Li}} \sim 2.5 \times 10^6$ K, and is therefore destroyed in stellar envelopes when stars possess deep (i.e. hot) surface convection zones. During the period of deep convection on the pre-MS, the temperature at the base of the convection zone surpasses $T_{\text{Li}}$ for FGK stars, inducing Deuterium depletion in the envelope (Iben 1965). This ‘standard model’ depletion terminates during the approach to the zero-age MS (ZAMS), when the convection zone retreats and again becomes cool. The magnitude of standard model depletion is extremely sensitive to the temperature at the base of the convection zone; it scales as $T^{20.5}$ for proto-stars (Bildsten et al. 1997). In standard stellar models (SSMs), only mass and composition influence this temperature, so equal mass stars within clusters are expected to reach the ZAMS with equal surface Li abundances, and remain nearly fixed in $A(Li)$ until the MS turn-off.

By contrast, Li abundance spreads have been observed in many stellar populations, such as the late G and K dwarfs on the pre-MS and ZAMS (e.g. Somers & Pinsonneault 2014, and refs. therein; SP14 hereafter), the mid-F dwarfs of 0.1–0.5 Gyr old clusters (e.g. Boesgaard & Tripicco 1986; Balachandran 1995), and solar analogues of old clusters and the field (Sestito & Randich 2005 and refs. therein; Israelian et al. 2009). Various non-standard processes have been put forward to explain the development of these dispersion, but they are generally unable to simultaneously explain all three above classes. For example, rotational mixing can induce depletion and dispersion on the MS, but cannot replicate the pattern in young stars (see below). Explaining this multifaceted Li depletion pattern presents a serious challenge for stellar evolution theory, but its resolution must reveal interesting physics not included in the standard model.

In this work, we investigate a potential cause of the Li dispersion developing on the pre-MS. This dispersion has been identified in several young clusters, such as Blanco 1 and $\alpha$ Per (Jeffries & James 1999; Balachandran, Mallik & Lambert 2011), but we focus solely on the most notable example, the Pleiades. The Pleiades is a nearby open cluster ($d \sim 133$ pc; An et al. 2007), just beyond the K dwarf ZAMS ($t \sim 125$ Myr old; Stauffer, Schultz & Kirkpatrick 1998), and with a near-solar

1 $A(Li) = 12 + \log_{10}(n(Li)/n(H))$
iron abundance ([Fe/H] \sim 0.03 \pm 0.02, Soderblom et al. 2009). The Pleiades also exhibits a significant, $T_{\text{eff}}$ dependent spread in the $\lambda$6708 Li I absorption feature, originally identified by Duncan & Jones (1983) and later confirmed by Soderblom et al. (1993). This EW dispersion suggests an abundance spread at fixed $T_{\text{eff}}$ of a few tenths of a dex at 6000K, which increases to greater than an order of magnitude below 5500K (Fig. 1). This dispersion has remained unexplained since its discovery, but an intriguing clue has motivated several attempts at resolution: the most Li rich stars at fixed $T_{\text{eff}}$ tend to be the most rapidly rotating in the K dwarf regime (Soderblom et al. 1993). This observation has led several authors to suggest that the dispersion results from various observational biases related to rapid rotation, such as the enhancement of the $\lambda$6708 Li I feature due to blending from rotational broadening (Margheim et al. 2002), large spot filling factors and chromospheric activity altering observed equivalent widths (Soderblom et al. 1993), and non-LTE effects (Carlsson et al. 1994). However, King et al. (2010) have shown that while these effects may contribute to the total dispersion, some underlying Li spread is likely present (see the discussion in §6.2 of SP14). It thus appears that some mechanism related to rotation affects Li depletion on the pre-MS.

The most widely discussed connection between rotation and Li is rotational mixing (e.g. Pinsonneault, Kawaler & Demarque 1990; Pinsonneault, Deliyannis & Demarque 1992; Zahn 1993; Chaboyer, Demarque & Pinsonneault 1995; Sestito & Randich 2003; Li et al. 2014). Theory predicts that chemical materials can be exchanged between layers in the interiors of rotating stars due to several hydrodynamic processes, such as Eddington–Sweet circulation (Eddington 1929; Sweet 1953; Zahn 1974). Through these mechanisms, Li-depleted material from the deep interior can be mixed into the convective envelope, diluting the surface abundance and decreasing A(Li) below the standard model predictions. Rotational mixing has been invoked to explain the progressive destruction of Li observed in MS open clusters (e.g. Pinsonneault 1997), because it operates over time-scales analogous to MS lifetimes (Pinsonneault, Kawaler & Demarque 1990), naturally predicts the development of Li dispersions within clusters, since depletion rates are determined by the non-uniform AM histories of individual stars (e.g. Irwin & Bouvier 2009), and decreases in efficiency at late ages due to stellar spin down, permitting the observed plateauing of Li abundances seen for old clusters (Sestito & Randich 2003).

While rotational mixing may be responsible for MS depletion, it is unlikely to produce the pattern seen in the Pleiades K dwarfs. Li depletion through rotational mixing is most efficient in rapid rotators, opposite to the sense of the Li–rotation correlation in the Pleiades. This implies that some stronger process related to rotation on the pre-MS must counteract the depletion of Li through mixing. Several such mechanisms have been suggested in the literature, such as stronger internal shears in slow rotators due to disparate core–envelope coupling times (Bouvier 2005), enhanced Li depletion in stars with extreme accretion histories (Baraffe & Chabrier 2010), and enhanced internal shears due to long disc-locking times in slow rotators (Eggenberger et al. 2012). We note that each of these mechanisms induces a Li dispersion by enhancing the depletion of slow rotators, whereas the empirical calibration of [SP14] favoured the suppression of depletion in rapid rotators.

SP14 proposed an explanation for the Pleiades Li dispersion that fit this criteria: a dispersion in stellar radii at fixed mass and age during the pre-MS. If the convective envelope of a star were inflated relative to standard predictions, the temperature at the base of the convection zone would be reduced. Li destruction in the envelope is a strong function of this temperature, so stars of dissimilar radii would undergo different rates of Li depletion during the pre-MS, and thus arrive at the ZAMS with unequal Li abundances. This effect is so strong that a pre-MS radius spread of ∼10 per cent in non-rotating models produces a greater than order-of-magnitude spread in Li at the ZAMS (SP14, fig. 14), and if the most inflated stars were also the most rapidly rotating, the observed Li–rotation correlation would be naturally produced.

This idea was motivated by the rapidly-growing literature on discrepancies between the precisely measured radii of stars and the predictions of modern stellar evolution codes. Accurate radius measurements (∼1–3 per cent) can be obtained by analysing the light curves of detached eclipsing binaries (e.g. Popeij 1997; Torres et al. 2010), and by measuring the angular diameter of nearby stars with interferometry (e.g. Bovajian et al. 2012). The average radii of open clusters can also be inferred by statistically modelling projected radius measurements ($R \sin i$; Jackson, Jeffries & Maxted 2009; Jackson & Jeffries 2014). With each method, discrepancies between predicted and observed radii of ∼10 per cent have been found. These so-called ‘radius anomalies’ have been identified, and found to correlate with rotation, in the pre-MS cluster IC 348 (Cottaar et al. 2014), precisely as required by our theory (see §4). They have also been found in young MS clusters, including the Pleiades (Jackson & Jeffries 2014), and the magnitude of the discrepancy has been seen to correlate with chromospheric activity and rotation rate (López-Morales 2007; Clausen et al. 2009; Stassun et al. 2012; Stassun, Feiden & Torres 2014).

While SP14 showed that a ∼10 per cent radius dispersion on the pre-MS can produce a Li dispersion commensurate with the Pleiades pattern, their analysis neglected the impact of rotational mixing. Mixing-driven Li destruction is strongest in rapid rotators, so this effect could cancel out to some degree the inflationary inhibition of Li destruction if these stars are the most inflated. We therefore extend our prior work by simultaneously calculating the effects of rotational mixing and radius inflation on Li depletion. When these calculations are complete, we find that the important qualitative features of the Pleiades Li and rotation pattern are gener-
ically produced if radius inflation is correlated with rotation in the proto-stellar domain.

The paper is organised as follows. In §2 we describe the machinery of our evolution code, the methodology of our approach, and the construction of our comparison data set. §3 describes the impact of inflation and rotation on our stellar models, with a particular emphasis on Li abundance and $T_{\text{eff}}$. §4 then tests various mappings between rotation and inflation, and compares the resulting distributions to the Pleiades. Several limiting cases are ruled out, and a special case where faster rotation leads to greater inflation is shown to compare favourably with the Pleiades. In §5 we explore plausible inflation mechanisms, assess the validity of the assumptions in our models, and suggest an observational test. Finally, §6 summarises the paper and restates our conclusions.

2 METHODS

The first step in our investigation is to generate a grid of stellar models with dimensions of mass, radius anomaly, and initial rotation conditions. Once complete, we can explore the generic behaviour of the models, and determine their ability to reproduce the Li–rotation correlation seen in the Pleiades. In this section, we first describe the stellar evolution code we employ, our basic calibration procedures, and our treatment of radius inflation. Next, we describe the implementation of rotation in our models. Finally, we assemble literature data for the Pleiades, as an empirical test of our models.

2.1 Standard model calibration and radius inflation

Stellar models were calculated using the Yale Rotating Evolution Code (YREC; see Pinsonneault et al. 1989 for a discussion of the mechanics of the code). We adopt a present day solar heavy element abundance of $Z/X = 0.02292$ from Grevesse & Sauval (1998), and choose the hydrogen mass fraction ($X$) and the mixing length coefficient ($\alpha_{\text{ML}}$) that reproduce the solar luminosity and radius for a 1$\odot$ model at 4.568 Gyr. The final solar calibrated values are $X = 0.71304$, $Z = 0.018035$, and $\alpha_{\odot} = 1.88166$. Our models use the 2006 OPAL equation of state (Rogers, Swenson & Iglesias, 1996, Rogers & Nayfonov, 2002), atmospheric initial conditions from Kurucz (1979), high temperature opacities from the opacity project (Mendoza et al. 2007), low temperature opacities from Ferguson et al. (2005), the $^{7}\text{Li}(p, \alpha)$ reaction cross-section, and the cross-sections of other nuclear reactions from Adelberger et al. (2011). We treat electron screening using the method of Salpeter (1954), and do not include diffusion, as the timescales of this process are very long compared to the ages of systems we are concerned with. Our models are initialised with a Li abundance equal to the proto-solar abundance $\text{A}(\text{Li}) = 3.31$ (Anders & Grevesse 1989).

We model radius inflation in this paper as a product of magnetic activity. A strong magnetic field in the envelope of a low mass star can inhibit the efficiency of convection, resulting in a larger radius. We model this effect by reducing the mixing length parameter $\alpha_{\text{ML}}$, as suggested by Chabrier, Gallardo & Baraffe (2007). We discuss alternative physical inflation mechanisms in §5 but believe the forthcoming results hold regardless of the underlying cause, as long as a correlation between rotation and inflation exists. Using the solar calibrated mixing length $\alpha_{\odot}$, we calculated a baseline set of non-rotating models, with masses varying from 0.7$M_{\odot}$ to 1.2$M_{\odot}$ in steps of 0.05$M_{\odot}$, corresponding to the range of Pleiades members considered in this paper. These models are treated as possessing a radius anomaly of 0 per cent. We then define the function $\delta_{R}(M, \alpha_{\text{ML}})$ as the fractional difference between the solar calibrated radius, $R(M, \alpha_{\odot})$, and the radius of another model of equal mass but mixing length $\alpha_{\text{ML}}$.

$$
\delta_{R}(M, \alpha_{\text{ML}}) = \frac{R(M, \alpha_{\text{ML}}) - R(M, \alpha_{\odot})}{R(M, \alpha_{\odot})}.
$$

(1)

This value is calculated at 10 Myr, an age characteristic of the epoch of pre-MS Li depletion in solar analogues, because $\delta_{R}$ varies with time during the pre-MS (SP14). Next, we determined the $\alpha_{\text{ML}}$ necessary to inflate a model of each mass to $\delta_{R}(M, \alpha_{\text{ML}}) = 0.02$, 0.04, 0.06, 0.08, and 0.10, corresponding to radius anomalies of 2–10 per cent. The resulting values are shown in Fig. 2. A maximum anomaly of 10 per cent was chosen to coincide with the claimed radius anomalies in the Pleiades (Jackson & Jeffries 2014) and the upper envelope of anomalies observed in detached eclipsing binary systems and interferometric targets (see §1).

We note that pre-MS Li depletion in stellar models is highly sensitive to the input physics. SP14 showed that adopting different published physical inputs, such as the equation of state or the $^{7}\text{Li}(p, \alpha)$ reaction cross-section, can produce significant changes in the expected pre-MS depletion of stars 0.9$M_{\odot}$ and below. However, Li depletion on the MS is insensitive to physical inputs, so MS depletion predictions are robust once pre-MS depletion is correctly predicted. To address this issue, SP14 performed an empirical calibration of their models using the warm ($T_{\text{eff}} > 5500\text{K}$) stars in the Pleiades (see SP14 §3–4 for details), and derived systematic corrections to the ZAMS Li abundance as a function of $T_{\text{eff}}$. The corrections range from $\sim$0.2 dex in A(Li) at 6000K to $\sim$1 dex at 5000K. In this work, we apply these ‘empirically calibrated’ pre-MS Li depletion corrections to our models.

2.2 Rotation and angular momentum evolution

To initialise rotation, we first evolve non-rotating models down the Hayashi track to the deuterium birth line, defined as the age at which 1 per cent of the initial D abundance has been destroyed ($\sim$0.1 Myr for the Sun). At this age, the launch conditions are applied. We assign an initial rotation period $P_i$, and assume this period to be

![Figure 2. The mixing length parameters $\alpha_{\text{ML}}$ required to produce a radius anomaly $\delta_{R}$ at 10 Myr, as a function of mass (see §2.1).](image-url)
fixed for a specified time $\tau_{\nu}$, though magnetic interactions with a circumstellar disc (e.g. Koenigl 1991). Thereafter the rotation rate evolves under the influence of AM loss at the surface through magnetised winds. To model the loss of angular momentum, we adopt a modification of the wind law of Kawaler (1988), first proposed by Krishnamurthi et al. (1997). In this formulation, the rotation rate increases with the cube of the angular velocity, up to a critical ‘saturation’ threshold $\omega_{\text{crit}}$, when the loss law becomes linear with $\omega$. This formulation leaves us with three free parameters to calibrate: $F_K$, $\omega_{\text{crit,} \odot}$, and $f_c$. The two rotation parameters are $\omega_{\text{crit}}$ and $\omega_{\text{crit,} \odot}$, which are evident in all photometric bands.

Here, $I/M$ is the moment of inertia per unit mass, $D$ is the convective overturn time-scale divided by the angular velocity, up to a critical ‘saturation’ threshold $\omega_{\text{crit}}$, when the loss law becomes linear with $\omega$. The saturation threshold $\omega_{\text{crit}}$ is scaled by the Rossby number (rotation period $P_{\text{rot}}$ divided by the convective overturn time-scale $\tau_{\nu}$) of each model, which is normalised on the Sun. The formula is given by Eq. (2):

$$\frac{dJ}{dt} = \left\{ \begin{array}{ll}
F_K \left( \frac{R}{R_{\odot}} \right)^{\frac{3}{2}} \left( \frac{M}{M_{\odot}} \right)^{\frac{1}{2}} \left( \frac{\omega_{\text{crit}}}{\omega_{\odot}} \right)^2, & \omega_{\text{crit}} < \omega < \frac{\tau_{\nu}}{\tau_{\nu}, \odot} \\
F_K \left( \frac{R}{R_{\odot}} \right)^{\frac{3}{2}} \left( \frac{M}{M_{\odot}} \right)^{\frac{1}{2}} \left( \frac{\omega_{\text{crit}, \odot}}{\omega_{\odot}} \right)^2, & \omega_{\text{crit}, \odot} \leq \omega \leq \frac{\tau_{\nu}}{\tau_{\nu}, \odot}
\end{array} \right. \tag{2}$$

$F_K$ represents the normalisation of the magnetic field strength, which is typically calibrated to reproduce observational data. Convection zones are assumed to rotate as a solid body, whereas radiative zones conserved angular momentum locally. The redistribution of angular momentum and chemical species throughout the radiative zones of star occurs purely through hydrodynamic instabilities in these models (e.g. Endal & Sofia 1978), and are calculated by solving the coupled differential equations:

$$\frac{\rho r^2 I}{M} \frac{d\omega}{dt} = f_\nu \frac{d}{dr} \left( \frac{\rho r^2 I}{M} \frac{D}{D \omega} \frac{d\omega}{dr} \right), \tag{3}$$

$$\frac{\rho r^2 dX_i}{dt} = f_c \frac{f_\nu}{f_r} \frac{d}{dr} \left( \rho r^2 \frac{D}{D X_i} \frac{dX_i}{dr} \right). \tag{4}$$

Here, $I/M$ is the moment of inertia per unit mass, $D$ is the characteristic diffusion coefficient of the angular momentum redistribution process, $f_\nu$ is a scaling factor that sets the efficiency of this transport ($f_\nu = 1$ in our models), and $f_c$ is a scaling factor that sets the efficiency of transport of chemical species $X_i$, relative to $f_\nu$. (Chaboyer & Zahn 1992). A strong assumption of this treatment is that AM transport operates purely through hydrodynamic instabilities. We discuss this assumption in (5) and conclude that it does not alter our results.

This formulation leaves us with three free parameters to calibrate: $F_K$, $\omega_{\text{crit,} \odot}$, and $f_c$. The two rotation parameters are $\omega_{\text{crit}}$ and $\omega_{\text{crit,} \odot}$. To determine the quality of fit, we summed in quadrature the difference between the empirical M37 median and upper envelope of the 550 Myr old M37 rotation distribution, from 0.6$M_{\odot}$ to 1.0$M_{\odot}$ (Hartman et al. 2005). We do this by first calculating the rotation rate of the 50th and 90th percentile of rapid rotators in the M37 catalogue, as a function of $T_{\text{eff}}$. We then evolved rotating models with median initial conditions ($\tau_{\nu} = 3$ Myr, $P_{\text{rot}} = 8$ days) and fast initial conditions ($\tau_{\nu, \odot} = 0.1$ Myr, $P_{\text{rot}} = 8$ days) to 550 Myr, with a variety of values for $F_K$ and $\omega_{\text{crit,} \odot}$. To determine the quality of fit, we summed in quadrature the difference between the empirical M37 median and upper envelope and our model predictions, and adopted the values of the best fit. This method was chosen over the more standard solar calibration because we are concerned in this work with early stellar evolution, and a rotation anchor temporally closer to the epoch we are studying provides a more robust calibration. With the rotation parameters set, $f_c$ was determined by requiring a median rotating solar mass model to match the median, metallicity-unbiased Li measurements of the Hyades from SP14, a cluster of similar age to M37. Our final values are $F_K = 3.3$, $\omega_{\text{crit,} \odot} = 9.5\omega_{\odot}$, and $f_c = 0.05$. The latter is consistent with typical results for rotational mixing calculations in the literature (e.g. Pinsonneault, Kawaler & Demarque 1990) and with anisotropic turbulence expected from theory (Chaboyer & Zahn 1992).

With the necessary values of $\alpha_{\text{ML}}$, in hand, and the angular momentum and chemical transport calibrated, we calculated a grid of solar metallicity models, with dimensions of mass (0.7–1.2$M_{\odot}$) and $\delta_{\text{r}}$ (0.0–0.1), for a variety of initial rotation conditions. Each star was given an initial period of 8 days at the deuterium birth line, and we range disc-locking times from 0.1 Myr, which corresponds to the most rapidly rotating stars in the 13 Myr open cluster h Per (Moraux et al. 2013) to 6 Myr, corresponding to the observed upper limit of disc survival lifetimes (Haisch, Lada & Lada 2001; Fedele et al. 2010). Each model was evolved to the age of the Pleiades, so that the resulting distribution could be compared with the observational pattern.

### 2.3 Pleiades data

We use literature observations of the Pleiades to construct a data set of $T_{\text{eff}}$, $A$(Li), and $P_{\text{rot}}$, for comparisons with our models. Our initial sample is composed of stars with $6707.8$ Li I equivalent widths from Soderblom et al. (1993). We use photometry to estimate $T_{\text{eff}}$, but note that it is challenging to infer $T_{\text{eff}}$ for heavily spotted stars, as strong temperature inhomogeneities impact both photometric and spectroscopic diagnostics. The Pleiades K dwarfs are known to show colour abnormalities possibly related to surface magnetic activity, radius inflation, and spot stars (Jones 1972, van Leeuwen, Alpenaar & Moyal 1987; Stauffer et al. 2003). This effect tends to push $B - V$ bluer and $V - K$ redward, but has a relatively small effect on $V - I$. (Stauffer et al. 2003). Unfortunately, several members of the Soderblom et al. (1993) sample do not have published $I$-band photometry, so we elect to take an average of the parameters derived from $B - V$ and $V - K$. This choice does not impact the salient qualitative features of the Pleiades pattern, which are evident in all photometric bands.

We cross-correlated our sample with the catalogue of Pleiades members assembled by Stauffer et al. (2007), and extracted $B$, $V$, and $K$ band photometry for each. We adopt $E(B - V) = 0.04$ for the stars in our sample (e.g. Soderblom et al. 1993), with the exception of a few members with abnormally high extinction, for whom we adopt the individual $E(B - V)$ values suggested in table 9 of Soderblom et al. (1993). From these values, $E(V - K)$ was derived assuming an $RV = 3.1$ extinction law (Cardelli, Clayton & Mathis 1989). Using these parameters, we calculate effective temperatures using the $B - V$ and $V - K$ polynomial fits to the infrared flux method calibration of Casagrande et al. (2010), and Li abundances using the curves of growth of Soderblom et al. (1993). With these values calculated, we averaged the $T_{\text{eff}}$s and $A$(Li)s derived from the two photometric bands to obtain the final stellar parameters. We compared these values to the Pleiades parameters from SP14, which were derived using just $B - V$ photometry. The result is a RMS difference of $\Delta T_{\text{RMS}} = 44$ K and $\Delta A$(Li)$_{\text{RMS}} = 0.05$ dex between the two data sets for stars hotter than 5250 K ($B - V = 0.87$), and $\Delta T_{\text{RMS}} = 107$ K and $\Delta A$(Li)$_{\text{RMS}} = 0.14$ dex for stars cooler than 5250 K. This demonstrates that spots have a stronger impact on the derived parameters of lower mass stars, but the small RMS compared to the range of values in Fig. confirms that the large dispersion cannot result from random photometric errors alone. Finally, we cross correlated our sample with the Pleiades
rotation catalogue of [Hartman et al. 2010]. The result is a data set of 97 Pleiads ranging in temperature from 4300–6200K, in rotation period from $P_{\text{rot}} = 0.25$ to 9 days, and in A(Li) from 0.3 to 3.4.

3 THE IMPACT OF ROTATION AND INFLATION

In §2 we described the construction of a grid of stellar models with dimensions of mass (0.7–1.2 $M_\odot$), disc-locking time (0.1–6 Myr), and radius anomaly (0–10 per cent). In this section, we use this grid to explore the impact of inflation and rotation on the destruction of Li during the pre-MS. We begin by reviewing the individual consequences of these two effects on stellar Li abundances in §3.1, §3.2

Rapid rotation is shown to enhance the rate of Li depletion due to the strong influence of rotational mixing, and radius anomalies are shown to inhibit the rate of Li depletion due to a decreased temperature at the base of the convection zone. Next, we investigate models with both rotation and inflation in §3.3. The result is complicated: Li depletion can either increase or decrease compared to a standard benchmark (no inflation, no rotation) depending on the relative strength of the two effects. In particular, we find that if a connection between rotation and inflation is present, Li depletion tends to correlate with rotation in cool stars and anti-correlate with rotation in hot stars. This motivates an exploration of the observational signature of different plausible inflation/rotation relationships in §4.

3.1 Rotation

In the theory of rotational mixing, meridional circulation and internal shears transport material between layers, leading to a gradual dilution of the envelope with Li-depleted material from the deep interior. Stars are born with a range of initial rotation conditions, so the rate of mixing differs from star to star in young systems, leading to the emergence of Li dispersions. Over 0.5–5 Gyr, both the internal and external rotation rates of stars converge, equalising the rate of Li depletion between stars with different AM histories; this freezes out the spread present at this age. Throughout stellar lifetimes, the strength of mixing depends on the absolute rotation rate of the star and on the degree of differential rotation within the star. This makes Li depletion efficient at young ages and inefficient at old ages, since both stellar surfaces and interiors spin down over time. This generic picture of MS rotational mixing has been long established, but we are concerned in this work with the effect of rotation on the pre-MS, which is often neglected in mixing studies due to its small assumed effect relative to standard model depletion. We therefore present an exploration of the impact on rotation on Li during the proto-stellar phase.

The top left of Fig. 3 shows rotation tracks for several solar calibrated ($\delta R = 0.0$), 0.9$M_\odot$ models with different disc-locking times. The models remain at constant rotation period (8 days) until detaching from their discs, when pre-MS contraction begins to increase their rotation rate. Once the models fully contract on to the ZAMS ($\sim 50$ Myr), they begin to spin down under the influence of magnetic winds. Shorter disc-locking times lead to faster rotation at the ZAMS, given an equal initial rotation rate. Thus the observational result that disc lifetimes differ from star to star naturally implies a $> 1$ dex range of rotation periods at the ZAMS. We also plot as black crosses the rotation rates of all stars of mass 0.8–1.0$M_\odot$ from literature catalogues of the 13 Myr cluster h Persei [Moraux et al. 2013] and the Pleiades [Hartman et al. 2010], demonstrating that the range of rotation rates in our models are representative of the observed range.

The bottom left panel follows the evolution of Li in the envelope of each model. Three stages of pre-MS Li evolution are revealed: 1) no depletion for the first few Myr; 2) an epoch of depletion from $\sim 3$–20 Myr; 3) very little depletion on the late pre-MS. Thereafter, rotational mixing depletes Li on the MS. The second pre-MS phase represents the time when the temperature at the base of the convection zone surpasses the Li depletion temperature (see Fig. 1). The rate of Li destruction during this phase is a strong function of rotation, so depletion in rapid rotators is high. This is because rotational mixing is particularly efficient when the material directly below the convection zone is highly depleted, as is the case when convection zones are deep. We have also plotted the Li track of a standard, non-rotating model (black dashed line) for comparison. This model depletes nearly the same amount of Li during the pre-MS as the slow rotating models ($\tau_D \geq 1$ Myr), suggesting that very rapid rotation ($\lesssim 1$ day period) is necessary for an appreciable enhancement to the rate of pre-MS depletion.

The right column of Fig. 3 explores the mass dependence of this behaviour at the age of the Pleiades. In the top panel, each individual line represents a fixed disc-locking time, and the points signify mass steps of 0.05$M_\odot$, with the 0.9$M_\odot$ locus indicated by a dotted line. A large range of rotation rates persist at 125 Myr within our mass range. The rotation dispersion is largest below $\sim 5700$K, and decreases towards larger $T_{\text{eff}}$. We also see that the structural effects of rapid rotation lead to a reduction of the surface temperature by $\sim 50$–150K, independent of spot-induced changes. The bottom right panel shows Li isochrones at the age of the Pleiades. Lower mass stars undergo deeper convection during the pre-MS, and spend more time on the pre-MS, resulting in more rapid Li destruction over an extended period of time, and ultimately a lower abundance at 125 Myr. Variable rotation induces a Li dispersion commensurate with the 0.9$M_\odot$ spread at all masses in the considered range, suggesting that the 0.9$M_\odot$ Li tracks are representative of the behaviour of Li destruction in all of our models. Thus, our rotating models predict that at the age of the Pleiades, slow rotators should cluster near the standard prediction (dashed black line), and fast rotators should be depleted below the standard prediction by $\sim 1.5$ dex.

3.2 Inflation

Next, we assess the impact of radius inflation in the absence of rotational mixing. The left panel of Fig. 4 shows in colour the Li tracks of non-rotating 0.9$M_\odot$ models with a variety of radius anomalies. The three stages of pre-MS depletion described above persist in inflated models, but the magnitude of depletion in the second stage is found to be highly sensitive to the stellar radius. Inflation reduces the temperature at the base of the convection zone, suppressing the rate of Li proton capture reactions and leading to a higher ZAMS abundance. The non-inflated, rotating tracks from Fig. 3 are shown in dotted grey for comparison. While increasing rotation enhances the destruction of Li, increasing inflation inhibits the destruction of Li. Both effects induce a dispersion, but the rotationally-induced spread lies below the standard prediction, and the inflationary spread lies above the standard prediction. The inflated models show no signs of additional depletion once on the MS, due to the lack of rotational mixing.

The right panel shows inflated isochrones at the age of the Pleiades, with the 0.9$M_\odot$ locus denoted by the black dotted line. Li
dispersions emerge generically at all masses, as with rotation, but the magnitude of the dispersion imparted by inflation is a stronger function of temperature: the dispersion increases from \( \sim 0.92\) dex at 6000K to \( \sim 1.30\) dex at 5000K due to rotation, while increasing from \( \sim 0.26\) dex to 1.40 dex at the same temperatures due to inflation. Importantly, the dispersion at fixed \( T_{\text{eff}} \) is larger than the dispersion at fixed mass; radius anomalies substantially reduce the \( T_{\text{eff}} \) of stars, so the \( T_{\text{eff}} \) of inflated, higher mass, Li-rich stars can be equal to that of non-inflated, lower mass, Li-poor stars. Ultimately, we see that a spread in radii of 10 per cent during the pre-MS can produce a Li dispersion that is small at temperatures typical of early G stars (\( \sim 6000\)K), and increases to nearly two orders of magnitude at temperatures typical of mid K dwarfs (\( \sim 4500\)K). These results are qualitatively similar to the findings of SP14, who examined isochrones of constant mixing length instead of constant radius anomaly.

To summarise 3.1–3.2 increased rotation and increased inflation have the opposite effect for Li depletion: faster rotation leads to lower Li abundances, while higher inflation leads to greater Li abundances. Both effects can induce dispersions if they vary from star to star, but inflationary dispersions lie above standard predictions, and rotational dispersions lie below standard predictions. However, both effects serve to reduce stellar \( T_{\text{eff}} \)s below standard stellar model predictions.

3.3 Rotation and inflation

We now present models which include both rotation and inflation. In this section, we permit any combination of these two parameters, for the purposes of exploring their combined impact on Li. Fig. 5 compares the tracks of rotating models with a 10 per cent radius anomaly (dashed black; slowly rotating in the left panel, rapidly

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**Figure 3.** The impact of rotation on Li depletion in non-inflated models. Left: The evolution of the surface rotation period (top) and the envelope Li abundance (bottom) in 0.9\( \odot \) non-inflated models. A range of initial disc-locking times produces a range of Li depletion factors at the age of the Pleiades, which mainly set in between \( \sim 5\)–20 Myr. Faster rotation leads to greater depletion in these models. Right: Isochrones of rotation and Li at the age of the Pleiades. A large range of rotation rates persist at this age, given our initial rotation distribution. A Li dispersion forms at all temperatures in the models, and fans out below the standard prediction (black dashed line). A black dotted line shows the location of the 0.9\( \odot \) models represented in the left column.
rotating in the right) to three models from [31,32] a non-inflated, non-rotating model (solid grey), a model with a 10 per cent radius anomaly and no rotation (dashed grey), and a rapidly rotating model with no inflation (solid black; slowly rotating in left, rapidly rotating in right). The three comparison models exhibit the previously described behaviour: rotation enhances Li depletion, and inflation suppresses Li depletion, relative to the standard prediction.

In the left panel, the inflated slow rotator track (dashed black) is nearly identical to the inflated non-rotator track (dashed grey), suggesting that the inflationary suppression of Li destruction dominates when rotation is mild. By contrast, the right panel shows that rapid rotation induces significant extra depletion relative to the non-rotating case in the presence of inflation. The non-rotating, inflated model (dashed grey) is significantly more abundant than the rapidly rotating, inflated model (dashed black), which in turn is far more abundant than the rapidly rotating, non-inflated model (solid black). Interestingly, the final abundance of the rapidly rotating, inflated model (dashed black in right panel) is close to that of the slowly rotating, non-inflated model (solid black in the left panel). This demonstrates that the counteracting effects of rotational mixing and inflation can almost entirely cancel each other out with regard to Li destruction, allowing a rapidly rotating inflated star to possess the same Li abundance as a slowly rotating non-inflated star at the age of the Pleiades.

To explore the mass dependence of this behaviour, we present isochrones of slow and rapid rotation at 125 Myr in the left and central panels of Fig. 6. Our Pleiades data are also plotted as open circles, and the dashed line signifies the locus of 0.9M⊙ models. The slow rotating models make similar predictions to the inflated, non-rotating models presented in Fig. 4 again demonstrating that the structural and hydrodynamic effects of rotation are minimal at low angular velocity. The abundance spread resulting from a 10 per cent radius anomaly matches the Pleiades dispersion well, as did the non-rotating models of [31,32]. Compared to these models, the rapid rotating isochrones in the central panel are significantly depleted. The 0 per cent anomaly isochrone is so heavily depleted by rotational mixing that it lies far below the data. However, the inflation of the 10 per cent anomaly isochrone suppresses rotational mixing enough to approximately trace the locus of rapid rotators below ~ 5200K. This correspondence is driven in part by the suppression of Li depletion, and in part by the substantial reduction in the surface temperature of our models, demonstrated by the dotted line (0.9M⊙ locus).

Finally, the right panel of Fig. 6 reproduces the slow rotating, non-inflated isochrone from the left panel in purple, and the rapidly rotating, inflated isochrone from the central panel in peach. The result is intriguing: below ~ 5700K, the rapid rotators appear more abundant in Li than the slow rotators. This is the opposite sense from the pure rotation case, where faster rotation always leads to greater Li depletion, but the same sense as the pattern observed in the Pleiades. Furthermore, the dispersion is small around 5500K, but increases substantially towards lower temperatures until reaching nearly 2 dex at 4500K, also reminiscent of the empirical Pleiades pattern. This behaviour suggests that a radius inflation which increases with rotation may be able to both produce the correct sense of the Li–rotation correlation seen in the Pleiades, and accurately predict the width of the dispersion as a function of temperature. In order to assess this possibility, we will consider in the following section the observational patterns resulting from different functional dependencies of inflation on rotation.
Figure 5. Left: The simultaneous effects of inflation and slow rotation. A standard model (solid grey), an inflated non-rotating model (dashed grey) and a non-inflated, slowly rotating model (solid black) are compared to an inflated, slowly rotating model (dashed black). Inflation dominates the evolution of Li when rotation is negligible. Right: Same as left panel, except with rapid rotation instead of slow rotation. The depletion effects of maximal inflation (10 per cent) and maximal rotation ($\tau_D = 0.1$ Myr) nearly cancel each other out at the age of the Pleiades, as the inflated rapid rotator (dashed black) reaches a similar abundance as the standard model (solid grey) at 125 Myr. It is clear that both inflation and rotation can strongly influence Li depletion.

Figure 6. Pleiades-age isochrones for models with both inflation and rotation. Left: Slow rotating models with a variety of inflation factors. The Pleiades data from Fig. I are also plotted. The Li dispersion resulting from a 10 per cent anomaly in slow rotators matches the observed dispersion as a function of $T_{\text{eff}}$ well. Centre: Same as left panel, but with rapid rotation. The most inflated Pleiads coincide with the maximally inflated, rapidly rotating isochrones. Right: The slow rotating, non-inflated isochrone from the left panel and the rapidly rotating, maximally inflated isochrone from the central panel are reproduced, along with lines matching models of equal mass. Below 5500K, these models succeed at producing the inverted Li–rotation pattern, as seen in the Pleiades.

4 SLEUTHING THE ROTATION–INFLATION CONNECTION

In §3.3, we argued that certain qualitative features of the Pleiades Li pattern are predicted if rapidly rotating stars are inflated relative to their slow rotating counterparts. In this section, we explicitly test this idea by generating synthetic cluster distributions with a variety of inflation/rotation prescriptions, and comparing them to data. To construct these synthetic distributions, we first adopt a rule that explicitly links the degree of inflation to the initial disc-locking time ($\delta_R = \delta_R(\tau_D)$). Using this rule, we collapse our 3-dimensional model grid (mass, disc-locking time, inflation) into two dimensions (mass, disc-locking time) by interpolating between models of fixed $M$ and $\tau_D$, but variable $\delta_R$, to the location in parameter space where the inflation rule $\delta_R = \delta_R(\tau_D)$ is satisfied. The result is a specific mapping between each choice of $M$ and $\tau_D$, and the relevant observables, $T_{\text{eff}}$, A(Li), and $P_{\text{rot}}$.

Next, we randomly generate 200 stars from this mapping by drawing a $\tau_D$ from a flat distribution between 0.1 and 6 Myr, and an $M$ from a flat distribution between 0.7 and 1.2 $M_\odot$. We then interpolate within the collapsed grid to the specified $M$ and $\tau_D$, and extract the resulting $T_{\text{eff}}$, A(Li), and $P_{\text{rot}}$. Finally, we randomly gen-
\textbf{Figure 7.} Maps and synthetic distributions for the three limiting cases described in \textsection 4.1.4.3. The lines in the maps are equal mass, and the points represent different disc-locking times, whereas each point in the synthetic distribution represents a different randomly drawn mass and \( T_{\text{eff}} \). The size of each point reflects the rotation rate at 125 Myr, as indicated by the key in the upper right panel. Case I assumes that all stars, regardless of rotation, have solar calibrated mixing lengths. Case II assumes that all stars possess 10 per cent radius anomalies, as might be expected from uniform saturation. Case III assumes no correlation between rotation and inflation. Each of these cases fails to reproduce the observed pattern, shown in the upper right panel and represented by approximate envelopes in each of the figures (see \textsection 4.1.4.3 for details).

\section*{4.1 Case I: no inflation}

The first limiting case assumes that no inflationary process operates on the pre-MS, and all stars can be described with a solar calibrated mixing length – hence \( \delta R(P_{\text{rot}}) \equiv 0.0 \). This represents the fiducial prediction of stellar evolution theory. The top left panel of Fig. 7 contains the Case I ‘map’, which shows the values of \( A(\text{Li}) \), \( T_{\text{eff}} \), and \( P_{\text{rot}} \) resulting from each \( M \) and \( T_{\text{D}} \) grid point at the age of the Pleiades. In this plot, lines connect models of equal mass but different disc-locking time. The size of the points denote the rotation rate, and the black dashed lines mark the approximate envelope of Pleiades data (see upper right panel). Line colours alternate to ease the distinguishing of mass tracks. Just as in the pure rotation models of \textsection 4.1, the stars with the shortest disc-locking times attain the most rapid rotation by 125 Myr, and show the greatest degrees of Li depletion. The models bracket the lower envelope of the Pleiades distribution, but do not approach the upper envelope.

A synthetic distribution for this case, generated as described above, appears in the bottom left panel of Fig. 7. Both the median and the width of the the distribution are reasonably accurate above 6000K, but not below the solar temperature. The median abundance falls below the empirical median, since the majority of the models occupy a narrow band which overlaps the lower envelope of the Pleiades distribution. Furthermore, the distribution width falls to increase substantially towards lower \( T_{\text{eff}} \), as the empirical width.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Maps and synthetic distributions for the three limiting cases described in \textsection 4.1.4.3. The lines in the maps are equal mass, and the points represent different disc-locking times, whereas each point in the synthetic distribution represents a different randomly drawn mass and \( T_{\text{eff}} \). The size of each point reflects the rotation rate at 125 Myr, as indicated by the key in the upper right panel. Case I assumes that all stars, regardless of rotation, have solar calibrated mixing lengths. Case II assumes that all stars possess 10 per cent radius anomalies, as might be expected from uniform saturation. Case III assumes no correlation between rotation and inflation. Each of these cases fails to reproduce the observed pattern, shown in the upper right panel and represented by approximate envelopes in each of the figures (see \textsection 4.1.4.3 for details).}
\end{figure}
I and Case II suggestively bracket the observed data range. We note however that Case II has suppressed Li destruction and reduced the surface temperature. The right of their counterparts in Case I, demonstrating that inflation is caused by accretion (e.g. Baraffe, Chabrier & Gallardo 2009). Stellar radii adjust to accretion-driven changes in the mass and energy content over a Kelvin–Helmholtz time, which is shorter than the time-scale for Li depletion during the pre-MS. The precise initial core mass and accretion history could therefore impact the stellar radius at 10 Myr, and thus the magnitude of Li depletion. If inflation is caused by accretion and the accretion history is uncorrelated with rotation, this limiting case is a reasonable approximation.

The type of mapping presented for Cases I and II has no physical meaning for Case III, since a direct correlation between rotation and inflation does not exist in this scenario. Instead, we present just a synthetic distribution in the bottom right of Fig. 7. Unlike the previous two cases, the model dispersion now matches the empirical dispersion reasonably well. In particular, it increases from ∼0.5 dex at the solar temperature to ∼1.5 dex around 5000K, in excellent agreement with the Pleiades. The median of the pattern appears to track the empirical median as well. However, the rotation distribution does not correspond to the observed pattern. Since rotation and inflation are uncorrelated, we see far too many slow rotators at the top of the distribution, and far too many rapid rotators at the bottom. This is particularly apparent between 5000K and 4500K; only 1 of the approximately 16 slow rotators in the Pleiades has A(Li) > 2.0, whereas greater than 50 per cent of the slow rotators in the Case III simulation have A(Li) > 2.0. This suggests that without some correspondence between rotation and inflation, the Li–rotation correlation in the Pleiades cannot be produced, ruling out Case III.

4.2 Case II: uniform inflation

The second limiting case assumes a ‘saturated’ inflation law; all stars possess the same radius anomaly regardless of rotation rate – hence δ_R(τ_D) ∼ 0.1. Thus, each of our models has a 10 per cent radius anomaly. This scenario is consistent with Jackson & Jeffries (2014), who found that the average K dwarf radius in the Pleiades is ∼10 per cent larger than expected from isochrones calibrated on old, inactive stars. Furthermore, uniform δ_R on the pre-MS is supported by Preibisch et al. (2003) and Argiroffi et al. (2013), who found that nearly all stars in the pre-MS associations ONC and h Per are saturated, and might therefore have the same radius anomaly if magnetic field proxies correlate with inflation.

The upper middle panel of Fig. 7 shows the mapping for this scenario, and the lower middle panel shows the resulting synthetic distribution. The slowest rotating models tend to lie above and to the right of their counterparts in Case I, demonstrating that inflation has suppressed Li destruction and reduced the surface temperature. For the rapidly rotating stars, the decrease in T_eff is far more extreme, causing a strong shift to the right. The result is a substantial overlap of the mass tracks. This is not seen in the most massive tracks, since even the fastest rotators in these bins have spun down substantially by 125 Myr (see Fig. 3). The overall trend is a strong suppression of Li destruction in all stars, regardless of rotation.

The lower middle panel shows a sample synthetic distribution. As in Case I, the models occupy a band at fixed T_eff that is far narrower than the empirical pattern. Unlike Case I, the median abundance trend lies far above the empirical median, and traces the upper envelope of the Pleiades distribution. This signifies that a uniform suppression of depletion is too strong to reproduce the most Li-poor stars below ∼5500K. The location of the rapid rotating models approximately corresponds with the rapid rotators in the Pleiades, but remain more depleted than slowly rotating models. Once again, the qualitative features of the Pleiades pattern are not in general reproduced, ruling out uniform inflation from the epoch of pre-MS Li destruction to the present. We note however that Case I and Case II suggestively bracket the observed data range.

4.3 Case III: uncorrelated inflation

The final limiting case assumes that no direct correlation exists between rotation and inflation. In this instance, we do not explicitly define a relationship δ_R = δ_R(τ_D), but instead randomly draw τ_D from our grid range independent of another. A physical scenario corresponding to this limiting case is proto-stellar radius variations caused by accretion (e.g. Baraffe, Chabrier & Gallardo 2009). Stellar radii adjust to accretion-driven changes in the mass and energy content over a Kelvin–Helmholtz time, which is shorter than the time-scale for Li depletion during the pre-MS. The precise initial core mass and accretion history could therefore impact the stellar radius at 10 Myr, and thus the magnitude of Li depletion. If
anomalies may not be constant during the pre-MS, our results are not significantly affected since only the radius at ∼10 Myr has an impact on the ZAMS Li abundance.

While this formulation is admittedly ad hoc, its features are motivated by data. Rapidly rotating, magnetically active stars tend to show the greatest deviations from standard models (e.g. López-Morales 2007), whereas slowly rotating, inactive stars generally agree with stellar models. This suggests that measurable inflation sets in above a critical rotation rate ($P_{0\%}$). A power law form was motivated by the power law dependence of chromospheric activity on rotation (e.g. Pizzolato et al. 2003). Our maximum anomaly was chosen to coincide with the upper envelope of claimed anomalies in the literature, as previously stated. Finally, a radius/rotation correlation has been claimed in some pre-MS open clusters (Cottaar et al. 2014). While this formulation has several free parameters, we will demonstrate that our results do not require a fine tuning of their values.

With this methodology, we first test a linear scaling ($\beta = 1$), with a transition period $P_{0\%} = 2$ days. This version of Eq. 5 is shown in blue in the top left of Fig. 8 and the corresponding mapping between $\tau_D$ and $\delta_R$ is shown in red. The bottom left panel shows the map for Case IV. The behaviour of the models is striking. Unlike Case I and II, where a shorter $\tau_D$ always results in a lower abundance, the response of Case IV models to shorter $\tau_D$s is mass dependent. Higher mass models (e.g. 1.2$M_\odot$) always cool down and deplete more with greater rotation, whereas lower mass models (e.g. 0.8$M_\odot$) show a more complicated relation. For long $\tau_D$ greater rotation induces more depletion, since none of these models is inflated in our present mapping. For intermediate $\tau_D$ greater rotation actually inhibits depletion, since intermediate rotation ($\tau_D$...
~ 0.7 Myr) has a smaller effect on Li depletion than intermediate
inflation ($\delta R \sim 0.05$; see Fig. 4). Finally for short $\tau_D$, mixing again
dominate, and the Li abundance decreases with faster rotation. The
overall trend is that shorter disc-locking times drive the models to
the upper right of this figure, and increase their Pleiades-age rota-
tion rate.

A Case IV synthetic distribution appears in the bottom right.
Unlike the first three cases, several salient qualitative features of
the empirical distribution are reproduced by this mapping. First, the
locus of slow rotators roughly corresponds to the lower envelope of
the Pleiades distribution, just as in Case I. This is to be expected,
as the Case IV slow rotators deviate from the standard picture the
least, and should therefore closely mimic the fiducial predictions.
Second, the most rapid rotators lie above and to the cool side of
this locus, roughly corresponding to the locus of rapid rotators in
the empirical pattern, as in Case II. This impression is driven in part
by the decreased rate of Li destruction on the pre-MS, and in part
by the reduced $T_{\text{eff}}$ of rapid rotators. Third, a significant dispersion
sets in around 5500K and increases towards cooler temperatures,
in excellent agreement with the Pleiades. One can understand why
this occurs at 5500K from the Case IV map. Rapid rotation moves
stars horizontally towards cooler temperatures in this figure; this
horizontal path coincides with the slow rotators above 5500K, but
lies above the slow rotators at lower temperatures, since these stars
are strongly depleted. The cool-ward motion of stars is of a similar
magnitude regardless of the mass, but the effect on the observed
distribution is more apparent in the sub-solar regime.

Despite the ad hoc nature of our $\delta_R(P_{\text{rot}})$ scaling, this model
succeeds at accurately predicting several puzzling features of the
observed Pleiades distribution. However, one could reasonably
contend that fine tuning may be required to achieve this qualitative
agreement. To address this concern, we assess the generality
of the Case IV agreement by calculating synthetic cluster distribu-
tions resulting from different choices of $\beta$ and $P_{0\%}$ in Eq. 5
and display them in Fig. 9. From left to right we increase the power
law exponent ($\beta$), and from top to bottom we decrease the rotation
rate at which inflation sets in ($P_{0\%}$). From this plot, we see
that some features of the Case IV mapping are generic, such as the
population of rapid rotators to the upper right of the main locus of
slow rotators, and the onset of dispersion at ~ 5500K. Other features
of the MC pattern vary from mapping to mapping, such as the
mixture between the upper right and left envelopes of the
Pleiades initial conditions. Since the important qualitative features
of the Pleiades pattern are generically reproduced, we conclude that fine tuning is not essential for the results of this section, given the sensitivity on the rotation initial conditions of the cluster.

To summarise [42x638] the three qualitative features of the empirical pattern described at the beginning of [444x638] are reproduced by a relationship between rapid rotation and inflation, and these qualitative features are largely insensitive to the exact choice of mapping function. We conclude that Case IV strongly outperforms each of the limiting cases, and produces an observational pattern consistent with the Pleiades.

5 DISCUSSION

We have presented the first consistent physical model that replicates the qualitative pattern of Li and rotation observed in the Pleiades. [42x638] delineated the properties of a successful solution, so we now turn to plausible explanations for the rotation-inflation correlation that we have modelled. We consider both the inhibition of convection by magnetic fields, and the impact of mass accretion during the proto-stellar phase. Next, we demonstrate that our results are not sensitive to the treatment of angular momentum transport in the interiors of our models. Finally, we discuss a method for detecting radius dispersions on the pre-MS and beyond, as a test of our scenario and as a means to constrain the putative connection between rotation and inflation.

5.1 The mechanism of inflation

Our paradigm assumes the existence of a mechanism which reduces the temperature at the base of the convection zone across the observed range of rapid rotators on the pre-MS. This behaviour naturally results from an increase in the stellar radius, so we have developed our models in the context of radius anomalies correlating with rotation. Inflated radii suppress both direct destruction of Li in convective envelopes and depletion driven by early rotational mixing, as we have demonstrated. There is observational support for this effect: in the 6 Myr old cluster IC 348, [444x638] detected a dispersion in radii of $\sim 25$ per cent at fixed $T_{\text{eff}}$, and found that stars with the largest radii tended to be the fastest rotating. Similarly, [444x638] found a correlation between luminosity and rotation at fixed $T_{\text{eff}}$ in the pre-MS associations Cepheus OB3b, NGC 2264, NGC 2362, and the Orion Nebula Cluster, indicative of behaviour analogous to IC 348. Finally, several pre-MS eclipsing binaries have been shown to have anomalous radii and temperatures, indicative of the behaviour we have described [Stassun, Mathieu & Valenti 2007; Stassun, Feiden & Torres 2014]. While it appears that radius dispersions correlating with rotation are present in some young systems, it remains unknown what induces this effect. In this section, we suggest two possibilities.

We have modelled radius inflation as a product of inhibited convective efficiency. This may result as a direct consequence of rapid rotation, when extreme Coriolis forces begin to govern the behaviour of convective particles (e.g. Miesch et al. 2001), but we focus on the suppression of convection produced by rotationally-generated magnetic fields. Magnetic fields in the envelopes of low mass stars can disrupt the motions of charged particles when they attempt to cross field lines. This leads to an increase in the convective energy flux per unit area in the non-magnetic regions, forcing the radius to expand in order to match the flux emanating from the core [Spruit 1982; Andronov & Pinsonneault 2004; Chabrier, Gallardo & Baraffe 2007; Feiden & Chaboyer 2013, 2014]. For instance, [444x638] found that the radii of several low mass eclipsing binaries, which are known to be inflated relative to standard predictions, could be reproduced with reasonable surface magnetic field strengths through the inhibition of convection. An important consequence of this effect is the formation of star spots on the surface, which result from the inefficient heat flux induced by magnetism. Several authors have taken this approach, and considered the impact of spots on the radii of stars (Chabrier, Gallardo & Baraffe 2007; Jackson, Jeffries & Maxted 2009; Jackson & Jeffries 2013, 2014). Polytropic models show that a filling factor of $\sim 0.35-0.51$ is sufficient to achieve a K dwarf inflation $\sim 10$ per cent, consistent with filling factors $\sim 0.2-0.4$ found on active G and K dwarfs (O’Neal et al. 2004). This behaviour appears particularly effective in stars with deep convection zones (Jackson, Jeffries & Maxted 2009), and so may be effective on the pre-MS. Magnetic fields can also provide pressure support in stellar interiors, thus working to counteract the force of gravity similar to rotational support (Mullan & MacDonald 2001; MacDonald & Mullan 2009, 2012, 2013). This phenomenon is fundamentally different from the inhibition of convection in that it adds an additional physical component instead of hampering an already present physical component (convection). Each of these effects serves to puff the radius up in stellar models, leading to a reduced temperature in the convection zone.

While these effects would naturally produce the type of correlation we require, activity studies of pre-MS clusters have found that most young stars of ages $\sim 1-15$ Myr are saturated, meaning that the strength of their magnetic field proxies (i.e. X-rays) no longer correlate with rotation rate [Preibisch et al. 2005; Argiroffi et al. 2013]. The predominate interpretation of this result is that magnetic fields cease to increase in strength beyond the critical Rossby number at which saturation sets in ($R_N = R_{\text{rot}}/T_{\text{CZ}} \sim 0.1$; Pizzolato et al. 2003). If true, it would appear difficult for convection to be progressively inhibited by rapid rotation among pre-MS stars. However, an alternative interpretation is that magnetic field proxies decouple from the strength of the surface field at the onset of saturation, so that magnetic fields can continue to grow with rotation without impacting proxies. For instance, saturation could represent a threshold above which chromospheric and coronal heating cannot increase, but the spot filling factor can. This would allow the convective efficiency to decrease with greater rotation, and not produce an observational signature in the classic proxies (e.g. O’Dell et al. 1995). Alternatively, the spot filling factor could approach unity when saturation sets in, but the spot temperature could continue to decrease with greater rotation, leading to a progressive inflation with no additional chromospheric or coronal emission. Several studies have attempted to measure directly the magnetic field strengths of saturated stars and have found mixed results (e.g. Saar 1996, 2001; Reiners, Basri & Browning 2009), but their efforts are hampered by the extreme difficulty of inferring Zeeman broadening from stars whose lines are already highly broadened by rotation (Reiners 2012). Due to these observational issues, the continued inhibition of convection with greater rotation in the saturated regime remains unresolved at present, but further work in this area will ultimately favour or disfavour this mechanism as a viable avenue.

Mass accretion may also play an important role in determining pre-MS radii. Proto-stars accrete the majority of their mass during the first $\sim 10^7$ yr, when the initial core of $M \sim 10^{-3}M_\odot$ gains material from the surrounding over-density in its natal molec-
ular cloud. Accretion likely progresses at a modest level \((10^{-8} - 10^{-7} \, M_\odot \, \text{yr}^{-1})\), interspersed with short bursts of vigorous accretion \((10^{-6} - 10^{-4} \, M_\odot \, \text{yr}^{-1})\) until the final mass is assembled (see Baraffe, Vorobyov & Chabrier 2012). A major unknown factor in accretion theory is the amount of thermal energy deposited by the accreted material during these intense accretion bursts. ‘Cold accretion’ scenarios assert that all of the thermal energy of accreted material is radiated away the the photosphere, so only mass (and not entropy) is added to the proto-star (Hartmann, Cassen & Kenyon 1997, and refs. therein). This additional mass leads to a contraction of the radius. Alternatively, ‘hot accretion’ scenarios suggest that a substantial fraction of the thermal energy of the accreted material is absorbed into the stellar envelope. This type of accretion can increase stellar radii, by adding to the entropy of the envelope (e.g. Pallà & Stahler 1992).

In either case, a dispersion in radii will arise from differing accretion histories, and may persist throughout the pre-MS due to the lengthy thermal readjustment times. This leads to a range of Li depletion efficiencies during the epoch of standard burning (Baraffe & Chabrier 2010). If hot accretion is accompanied by substantial angular momentum deposition, or if the rotation period of cold accretors remains fixed during radius contraction due to magnetic interactions with circum-stellar material, then the necessary rotation correlation will be likewise present. This scenario makes two interesting predictions. One, that the rotational history of stars is intrinsically linked to their accretion history. Two, that inflation is only a transient event on the pre-MS, and therefore will be gone by the age of the Pleiades. The debate in the literature about hot versus cold accretion scenarios remains unsettled (Baraffe, Chabrier & Gallardo 2008; Hosokawa, Offner & Krumholz 2011; Baraffe, Vorobyov & Chabrier 2012), so further work remains to determine precisely how accretion impacts stellar radii on the early pre-MS.

While these mechanisms are fundamentally different, their impact on the structure at the base of the convection zone will be analogous. Any increase in the stellar radius moves the base of the convection zone outwards, reducing the rate of depletion, and any decrease in the stellar radius has the opposite effect. We therefore believe that the results of §3 hold regardless of the underlying inflationary mechanism. Given recent efforts to probe the radius–rotation connection in young stars (i.e. Littlefair et al. 2011; Cottaar et al. 2014), constraints may soon be placed on the connection between these two properties during the pre-MS.

### 5.2 The treatment of angular momentum transport

Angular momentum transport can have a powerful impact on mixing. Efficient transport from the core to the envelope counteracts the loss of angular momentum at the surface due to magnetic winds, allowing stars to remain rapidly rotating well into their MS lifetimes and greatly increasing the strength and longevity of meridional circulation. However, this strong coupling tends to equalise the rotation rates of different layers, leading to a suppression of internal differential rotation and therefore a reduction in the efficiency of shear mixing. By contrast, if this transport is inefficient, the envelope will rapidly spin down under the influence of magnetic winds while the core remains rapidly rotating, suppressing the strength of meridional circulation and enhancing the rate of shear mixing. Thus, weakly and strongly coupled models produce qualitatively different mixing histories, and therefore make different predictions about the evolution of Li abundances over the lifetimes of stars.

Since the true behaviour of transport in stellar interiors remains unsolved, it is reasonable to test whether the results obtained in §3 are sensitive to our treatment. In our calculations, we have assumed a limiting case where angular momentum is conserved locally in radiative zones, convective zones rotate as a solid body, and only hydrodynamic processes operate. This paradigm neglects additional transport processes which may operate in stellar interiors, such as gravity waves or organised internal magnetic fields. We refer to these as `hydrodynamic' models (Pinsonneault et al. 1989). This class of models can reproduce certain features of the rotational evolution of stars, such as the slow and rapid rotating sequence of young clusters (Irwin et al. 2007; Bouvier 2008; Denissenkov et al. 2010; Gallet & Bouvier 2013), but fails to predict other features, such as the later evolution of rapid rotators, the tight convergence of surface rotation rates at late ages, and the solid body rotation profile of the Sun (e.g. Irwin & Bouvier 2009).

These shortcomings can be largely remedied in the solar regime by assuming that an additional transport mechanism operates in stellar interiors (Denissenkov et al. 2010; Gallet & Bouvier 2013; Somers & Pinsonneault, in prep). This additional transport would allow for a more rapid coupling of the core and envelope than pure hydrodynamic models. This is beneficial, as comparisons between evolutionary models and open cluster rotation patterns suggest core–envelope coupling time-scales of \(\tau_{\text{CE}} \sim 100\) Myr and \(\tau_{\text{CE}} \sim 10\) Myr respectively for slow and rapid rotators (Bouvier 2008). For slow rotators in particular, this coupling time is far shorter than is found in hydrodynamic models (e.g. Krishnamurthi et al. 1997). Suggested mechanisms, such as internal gravity waves, transport angular momentum between layers, but chemical material. Thus the transport process does not directly destroy Li, but instead affects the internal rotation profile, leading to a different depletion history by hydrodynamic mixing (e.g. Press 1981; Montalbán & Schatzman 2000; Talon & Charbonnel 2005).

Bouvier (2008) pointed out that a short core–envelope coupling time-scale for rapid rotators may have implications for Li depletion, since the homogenisation of surface and core rotation rates decreases internal differential rotation, thus suppressing the efficiency of shear mixing in the fastest spinning stars. While Bouvier (2008) argued that this effect could itself induce the Li–rotation correlation in the Pleiades, we note that rotational mixing calculations have consistently demonstrated that more rapid rotation leads to greater depletion regardless of internal transport (e.g. Pinsonneault, Kawaler & Demarque 1990). This is because meridional circulation, which depends on the absolute rotation rate, is an effective mixing agent in rapid rotators, and overcomes any reduction in shear mixing induced by rapid envelope spin down. It therefore appears implausible that rapidly rotating Pleiads could deplete an order-of-magnitude less than slow rotators without an accompanying structural effect like the radius anomaly.

Never the less, assessing whether this additional physical effect alters our conclusions allows us to check whether our limiting case assumptions about transport are reasonable. To this end, we calculate stellar models with a constant diffusion of angular momentum from the core to the envelope, which operates in addition to hydrodynamic instabilities. Our treatment of this process is analogous to that of Denissenkov et al. (2010): angular momentum is extracted from the core and redistributed in the envelope at a rate specified by the diffusion coefficient \(\nu_{\text{CE}} \, [\text{cm}^2 \, \text{s}^{-1}]\), which is a free parameter.

We adopt the limiting case where \(\nu_{\text{CE}}\) does not depend on the rate of rotation. This holds if the additional transport is, for instance, driven by convective motions, as is the case for gravity
waves. It is important to note that even if an equivalent $\nu_{CE}$ is chosen for slow and rapid rotators, the time-scale for core–envelope coupling need not be the same. This is because the rate of angular momentum transport in these models is a product of both hydrodynamic transport, which depends on rotation rate, and $\nu_{CE}$, which does not depend on rotation rate. Because hydrodynamic transport is extremely inefficient in slow rotators, $\nu_{CE}$ will dominate the transport of angular momentum. Conversely, hydrodynamic transport is very efficient in rapid rotators, so $\nu_{CE}$ will have only a minor effect. It is therefore reasonable to calibrate $\nu_{CE}$ to replicate the expected coupling time-scale of slow rotators given by [Bouvier (2008)], $\tau_{CB} \sim 100$ Myr. [Denissenkov et al. (2010)] recommends $\nu_{CE} \sim 2 \times 10^4$ cm$^2$ s$^{-1}$ for this value of $\tau_{CB}$.

With this additional ingredient, we calculate stellar models with masses of 1.0$M_\odot$ and 0.8$M_\odot$, and disc-locking times of 0.1 and 6 Myr, and compare the results to the hydrodynamic models of [Li2]. Overall, we find that the impact on Li depletion is negligible. Only an additional 0.03 dex of A(Li) is preserved for the rapidly rotating case, both at 1.0 and 0.8$M_\odot$. This value is small because rapid rotators efficiently redistribute angular momentum through hydrodynamics, so a small additional flux has a similarly small effect. For the slowing rotating models, an additional 0.06 dex is preserved for 0.8$M_\odot$, demonstrating that the impact of $\nu_{CE}$ is greatest on slow rotators, as argued above. However, we find that an additional 0.02 dex is destroyed in the slowly rotating 1.0$M_\odot$ model; this is the opposite sign of the other three models. This additional depletion is due to the enhanced rotation of the envelope in recoupling models, driven by the inflow of angular momentum from the core; this leads to stronger mixing during the pre-MS. We conclude from these examples that the impact of an observationally motivated additional transport mechanism on Li depletion are in general non-linear and complex, but small in magnitude.

As an extreme limiting case, we adopt a value for $\nu_{CE}$ an order of magnitude higher, which replicates the coupling time-scale for rapid rotators ($\tau_{Coup} \sim 10$ Myr) in the absence of hydrodynamic transport. For the fastest spinning stars, we find that an additional 0.3 dex of A(Li) is preserved at the age of the Pleiades for $M = 1.0M_\odot$, and only 0.2 dex of A(Li) for $M = 0.8M_\odot$. For the slow rotators, an additional 0.1 and 0.15 dex are preserved for $M = 1.0$ and 0.8$M_\odot$ respectively. An inspection of the synthetic distribution resulting from Case IV (Fig. 5) shows that even in this extreme case, such models would remain within the envelope defining the empirical Pleiades distribution. Concordance between the median and dispersion of the models and the empirical data therefore survives. On the other hand, Cases I–III remain inconsistent with the observed pattern. For Case I, an additional 0.1–0.3 dex of Li cannot bring the heavily depleted rapid rotators into agreement with the empirical pattern. For Case II, the slow rotators would need to destroy an implausibly large amount of Li ($\sim 1–2$ dex) between the ZAMS and 125 Myr to accord with observations. Furthermore, this case would predict heavy depletion across the mass function in slow rotators, whereas it is only seen below 5500K in the Pleiades. For Case III, the Li abundance of the rapid rotators increases, but the pattern would still retain far too many slow rotators near the upper envelope of the pattern.

From these arguments, we conclude that the Li–rotation correlation cannot be produced by angular momentum transport in the absence of inflation. Moreover, the qualitative results of [Li2] are unchanged by rapid recoupling of the core and envelope in our fastest rotating models. This exercise strengthens our conclusions, as they are shown to hold when a more observationally motivated treatment of angular momentum transport is considered.

5.3 Testing the inflation paradigm

Jackson & Jeffries (2014) demonstrated that the average radius of the Pleiades K dwarfs is inflates by $\sim 10$ per cent, but they did not attempt to characterise the distribution about this average. If a radius dispersion was present in the Pleiades at $\sim 10$ Myr, as required by our models, then a remnant of the dispersion might still exist today. Detection of a radius dispersion at 125 Myr would have important implications not only for the evolution of Li, but for the structure of stars on the pre-MS, the behaviour of saturated stars, and the effects of spots and magnetic fields on stellar radii.

A viable avenue for testing whether a spread is present in the Pleiades is through obtaining surface gravities for a large number of cluster members. If rapidly rotating Pleiads are physically larger than slowly rotating Pleiads, a dispersion in log $g$ at fixed colour arises due to three compounding effects. First, a radius increase of $\sim 10$ per cent naturally reduces the surface gravity ($g \propto M/R^2$) compared to non-inflated stars at fixed colour. Second, the most inflated stars are very rapidly rotating; rapid rotation further reduces $\tau_{diff}$ at fixed mass (Fig. 3), enhancing the effect. Third, since inflation reduces $\tau_{diff}$, the most inflated stars at fixed colour are also the most massive. Surface gravity decreases with increasing mass, because R is proportional to M in the solar regime ($g \propto M/R^2 \propto M/M^2 \propto 1/M$), leading to an additional reduction in the log $g$ of the most inflated (most massive) stars at fixed colour.

For a 10 per cent dispersion in radius, our models predict that the log $g$ dispersion could be as large as 0.2 dex at fixed colour. This signal may be detectable through granulation-induced light curve flicker [Bastien et al. (2013)]. The characteristic time-scale of the formation and dissolution of convective cells on the surface of stars is proportional to the surface gravity. This induces a correlation between the power of short time-scale luminosity variations and the strength of surface gravity, permitting the inference of stellar log $g$s with an accuracy of 0.1–0.15 dex (e.g. Bastien et al. 2013 2014). This signal can be extracted from high precision, long baseline, short cadence photometry, such as that obtained by the Kepler satellite. Although its mission has ended, Kepler’s descendant K2 will observe a field containing the Pleiades in early 2015 [Howell et al. (2014)], and despite the degraded photometric quality, may be able to detect granulation flicker at the necessary level. This offers a unique opportunity to detect and characterise the distribution of surface gravities, and search for a dispersion about the inflated mean. Although a positive detection provides circumstantial evidence in favour of our paradigm, we note that a radius spread is necessary at $\sim 10$ Myr to produce an anomalously driven Li dispersion. Thus log $g$ observations of a pre-MS cluster are required for definitive proof. None the less, since the pattern in our models results both from a decreased $\tau_{diff}$ and a decreased rate of Li depletion on the pre-MS, a detection or non-detection at 125 Myr places constraints on the degree of inflation required at 10 Myr to produce the present day spread. For example, if no radius dispersion remains today, then the observed spread must be driven entirely by differential Li abundances, and therefore a radius spread in excess of 10 per cent is necessary at 10 Myr. Alternatively, if the current radius spread exceeds 10 per cent, than the radius dispersion at 10 Myr necessary to achieve the observed Li dispersion may be less than 10 per cent.

This test will open the door for using Li abundances to understand differential pre-MS stellar structure, but much work remains to be done in order to correctly interpret the information. First, we must determine the mechanism driving the putative connection between rotation and inflation. If magnetic fields are responsible, how
do they impact stellar structure in the saturated regime? If accretion is responsible, is the cold or hot scenario more appropriate, and how do they impart the angular momentum distribution? If differential radius inflation on the pre-MS is not responsible for the observed Li depletion in all stars regardless of rotation, uniform radius inflation of 10 per cent in all stars regardless of rotation, and radius inflation uncorrelated with rotation. Next, we adopted a prescription where rapidly rotating stars are more inflated than slowly rotating stars, and found that observed pattern in the Pleiades is generically produced. The dispersion in Li remains small around the solar temperature and increases to greater than an order-of-magnitude towards cooler temperatures, precisely as is found in the Pleiades. Moreover, the median abundance trend is accurately predicted, and rapidly rotating stars are found to be more rich in Li than slowly rotating stars in the K dwarf regime. Furthermore, we find that these qualitative features are insensitive to the precise details of the rotation/inflation prescription we adopt as long as more rapid rotation leads to greater inflation, demonstrating that fine tuning is not required to achieve this level of agreement. This is the first consistent physical explanation for the Pleiades Li pattern to date, so we conclude that it is a strong candidate for explaining the observed pattern.

After establishing that a connection between rotation and inflation could explain the Pleiades pattern, we discussed what sort of physical mechanisms might lead to this correlation. The inhibition of convection due to strong magnetic fields in rapid rotators could lead to such a correlation if field strengths continue to grow with rotation in the saturated regime. Accretion could also alter the radii and rotational histories of proto-stars, plausibly inducing the observed correlation. We then demonstrated that our results are insensitive to the treatment of angular momentum transport in our models, strengthening our findings. Finally, we suggest that the remnants of a pre-MS radius dispersion may still be present in the Pleiades, and a survey of stellar surfaces gravities in this cluster could place strong constraints on the radius dispersion needed at 10 Myr to produce the observed pattern. The ongoing K2 mission offers a valuable opportunity to perform this experiment.

6 SUMMARY AND CONCLUSIONS

In this paper, we have explored the simultaneous impact of rotation and radius inflation on the depletion of lithium from stellar envelopes during the pre-MS. Our goal is to identify a viable physical mechanism for producing the well-known Li–rotation correlation in the K dwarfs of the Pleiades, which defies conventional theoretical predictions of the effect of rotation on Li depletion. Radius anomalies ~10 per cent are found in rapidly rotating, magnetically active stars (e.g. López-Morales 2007; Cottaar et al. 2014), and may have a strong impact on the depletion of Li during the pre-MS. This motivated us to test whether a correlation between rotation and radius inflation on the pre-MS could be responsible for the observed pattern.

We first reviewed the impact of rotation and inflation on the evolution of Li abundances. In accordance with previous studies, we find that the depletion of Li is a strong function of both properties, such that rotation increases the rate of Li destruction, and inflation decreases the rate of Li destruction. While this behaviour is straightforward, the picture becomes far more complicated when the two effects are combined. Rapid rotation and substantial radius inflation (10 per cent) enhances Li depletion for stars with $M > M_\odot$, but inhibits Li depletion for stars with $M < M_\odot$, relative to non-rotating benchmarks. This is the first new result of our work, and implies that if the radii of just the rapid rotators in the Pleiades were inflated by 10 per cent during the pre-MS, while the radii of the slow rotators agreed with standard predictions, then a positive correlation between the rate of rotation and the abundance of Li at 125 Myr could arise in K dwarfs, in agreement with observations.

Next, we assessed whether this qualitative notion could explain the observed relationship between Li and rotation in the Pleiades. To do this, we generated synthetic cluster distributions which obey various inflation/rotation prescriptions, and compared them to the empirical Pleiades pattern. First, we found that three limiting cases, which represent distinct classes of physical models, were unable to reproduce the Pleiades pattern: no radius inflation in all stars regardless of rotation, uniform radius inflation of 10 per cent in all stars regardless of rotation, and radius inflation uncorrelated with rotation. Next, we adopted a prescription where rapidly rotating stars are more inflated than slowly rotating stars, and found that observed pattern in the Pleiades is generically produced. The dispersion in Li remains small around the solar temperature and increases to greater than an order-of-magnitude towards cooler temperatures, precisely as is found in the Pleiades. Moreover, the median abundance trend is accurately predicted, and rapidly rotating stars are found to be more rich in Li than slowly rotating stars in the K dwarf regime. Furthermore, we find that these qualitative features are insensitive to the precise details of the rotation/inflation prescription we adopt as long as more rapid rotation leads to greater inflation, demonstrating that fine tuning is not required to achieve this level of agreement. This is the first consistent physical explanation for the Pleiades Li pattern to date, so we conclude that it is a strong candidate for explaining the observed pattern.
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