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Lithium in the young suns of Messier 35

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Abstract. Standard models for lithium depletion during the pre-main-sequence evolution of low-mass stars fail to explain the dispersion in abundance at a fixed $T_{\rm eff}$ among G- and K-type ZAMS stars. We have investigated this phenomenon in unprecedented detail using multi-object spectroscopy of a large sample of stars, with well-determined rotation periods, in the Pleiades-age cluster Messier 35. There is a clear correlation between fast rotation and reduced Li depletion at $T_{\rm eff} < 5500$ K. We show that this correlation is equally present in probable binary systems, that the correlation is not perfect, and provide evidence that the fast-rotating stars are also inflated compared to slow-rotating siblings at the same $T_{\rm eff}$. The observations provide some support for models of rotation-dependent magnetic activity that lead to suppressed convection, lower interior temperatures and less Li depletion in the faster rotators. Equally it leaves open the possibility that Li depletion is inhibited for all stars prior to the ZAMS, but that additional mixing subsequently depletes more Li in the slower rotators.

Key words. Stars: abundances – Stars: rotation

1. Introduction

Standard evolutionary models of young stars predict that Li depletion begins when a contracting pre-main-sequence (PMS) stars core reaches temperatures of 3×10^6 K. Photospheric depletion ensues, and only halts when all the Li has gone, or the base of the convection zone (CZ) falls below the Li-burning temperature. As a result, these models predict that Li depletion should be a well-behaved, single-valued, function of mass (or $T_{\rm eff}$). The reality is somewhat different; it is well known that Li-depletion, assessed by the strength of the Li 6708Å resonance line, shows a broad dispersion among young G- and K-type stars as they reach the ZAMS. These observations suggest there are mechanisms at work that may enhance or inhibit Li depletion, beyond the standard models (see review by Jeffries 2006).

The benchmark cluster for these studies has been the Pleiades (age 120 Myr). Decades ago it was recognised that a 2 order of magnitude spread in measured Li abundances developed between the hotter G stars to the cooler K stars (e.g. Duncan & Jones 1983; Soderblom et al. 1993). The evidence is strong that rotation plays a key role; there is a clear correlation between Li abundances and rotation, in the sense that the more rapidly rotating stars appear to have preserved more Li (Barrado et al. 2016; Bouvier et al. 2018).

M35 is a Pleiades analogue, which is more distant (800pc), slightly older (age ~ 150 Myr) and perhaps slightly metal-poor compared to the Pleiades. Its stellar Li content has been

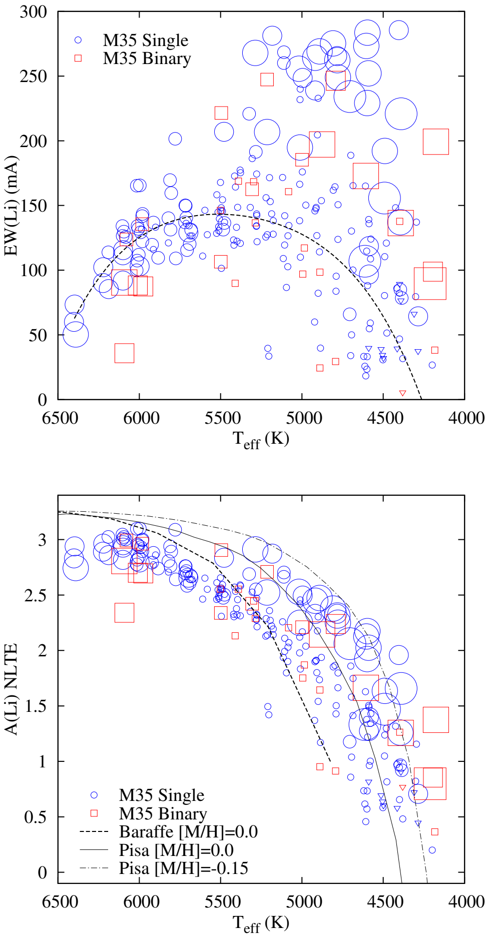

Fig. 1. (a) Li 6708Å equivalent widths and (b) inferred Li abundances for M35 members. Single stars and probable binaries are indicated. The symbol size is proportional to $\log_{10}$ of the angular velocity (rotation periods range from 0.3–10 d). The line in (a) is a quartic fit to the slowest rotating half of the sample. The lines in (b) are standard ZAMS Li depletion models from Baraffe et al. (2015) and the Pisa PROSECCO models at two metallicities (Tognelli et al. 2011).

investigated by Barrado y Navascués et al. (2001) and Anthony-Twarog et al. (2018) using relatively small samples. They found an Li abundance pattern similar to the Pleiades, but with a slightly lower mean and indications that the dispersion was smaller. M35 is however much richer than the Pleiades, so although more distant, has great potential for examining the Li-rotation connection among ZAMS stars in much more detail.

2. Observations

In November 2017, M35 was observed using the WIYN Hydra multi-fiber spectrograph. Targets were chiefly G- and K-stars with rotation periods measured by Kepler K2 or from ground-based observations (Meibom et al. 2009; Libralato et al. 2016).

We observed 342 candidate members with $14 < V < 18$, and used the spectra to measure Li 6708Å equivalent widths (EW(Li) – accounting for nearby blends) and single-epoch radial velocities (RVs). *Gaia* DR2 proper motions and the RVs were used to assign a membership probability to each target. The *Gaia* photometry along with 2MASS, WISE and BVRI photometry were used to construct SEDs, and modelled to estimate $L_{\rm bol}$ and $T_{\rm eff}$. A final sample of 242 kinematic members with rotation periods and SED fits was assembled. The expected number of contaminants is < 1. The HR diagram was used to estimate a relative "over-radius", R/R_0, at a given $T_{\rm eff}$ for each star, based on its displacement from a luminosity locus defined by the lowest luminosity quartile. i.e. $R/R_0 = \sqrt{10^{\Delta \log L}}$. Probable binaries were identified as those with $R/R_0 > 1.25$ ($\Delta \log L > 0.2$). Low mass-ratio binaries may still be present among the "single stars".

3. Lithium and rotation

Figure 1 shows EW(Li) and estimated NLTE Li abundances (A(Li)$= 12+\log(N[\mathrm{Li}]/[N(\mathrm{H}]))$ as a function of $T_{\rm eff}$ for "single" and "binary" members of M35. In each plot the symbol size is proportional to $\log_{10}$ of the rotation rate of the stars. The pattern identified in the Pleiades by Bouvier et al. (2018) is clearly seen in M35. For stars with $T_{\rm eff} < 5500$ K there is a growing dispersion in A(Li) and a close correlation between fast rotation and higher Li abundance at a given $T_{\rm eff}$. The overall scatter is much

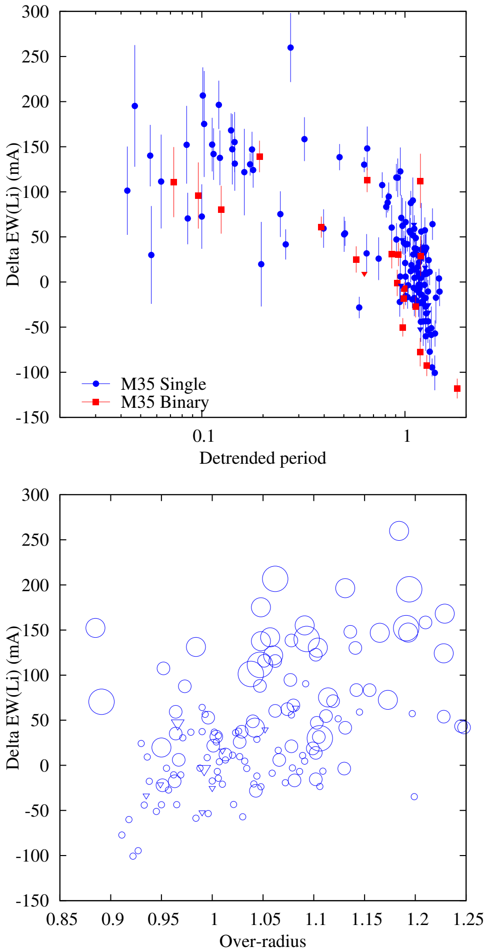

Fig. 2. Excess Li 6708Å equivalent width (with respect to the fiducial line in Fig. 1a), for stars with $4200 < T_{\rm eff} < 5500$ K, as a function of (a) detrended rotation period (see text, fastest rotators are on the left) and (b) the relative over-radius with respect to the low luminosity half of the HR diagram. The symbol size in (b) is proprtional to the log of the inverse Rossby number (the ratio of period to convective turnover time), which is expected to trace dynamo activity.

larger than the typical uncertainties in EW(Li) or $A(Li)$, of $\sim$ 20 mÅ and $\sim$ 0.1 dex respectively, and $T_{\rm eff}$ uncertainties are only $\sim$ 50 K. At hotter temperatures the dispersion decreases and becomes comparable with the uncertainties. The overall level of Li depletion in M35 and the amount of dispersion as a function of $T_{\rm eff}$ are very similar to the Pleiades.

Figure 1b also shows some theoretical predictions of Li depletion at the ZAMS (with $A(\rm Li)_{\rm initial} = 3.3$). These demonstrate that standard models, which only include mixing by convection, fail to reproduce the exact shape of the Li depletion pattern (and cannot explain the dispersion). Depending on choice of model and model assumptions (e.g. composition, mixing lengths, boundary conditions) the Li depletion predictions are quite different. It is thus difficult to say whether the dispersion of $A(\rm Li)$ among the cool stars is due to reduced Li depletion (compared to a standard model) in the fast rotators, enhanced Li depletion among slow rotators or a combination of both.

Figure 2a examines the lithium-rotation connection in more detail for M35 members with $4200 < T_{\rm eff} < 5500$ K. The y-axis is the "excess" ΔEW(Li) with respect to a fit to the median EW(Li) of the slowest rotating half of the sample (the line in Fig.1a). The x-axis is "detrended period", defined as the ratio of the observed rotation period to that of the "I-sequence" of slow rotating stars in the period vs $T_{\rm eff}$ plane. This plot contains about 2.5 times as many stars as an equivalent sample from the Pleiades and as a result shows two important features with robust statistics:

(a) Although the correlation between ΔEW(Li) and (detrended) rotation period is strong, it is not single-valued or without scatter. Although all fast rotators appear to have consistently depleted less Li, there are examples of slow and intermediate rotators that have similar or only slightly lower ΔEW(Li). It is unlikely that this can be explained by measurement uncertainties in EW(Li), rotation period or $T_{\rm eff}$.

(b) Stars identified as probable components of binary systems do not show markedly different behaviour to "single stars". Thus although there may be unrecognised binaries (with small mass ratios) in the "single" star sample, the mere fact that stars are part of binary systems does not appear to directly drive the correlation between lithium and rotation or the scatter that has been identified at a given rotation rate.

4. Discussion and conclusions

It has been hypothesised that the Li dispersion among ZAMS G- and K-stars is due to inhibited PMS depletion among fast-rotating stars, caused by inflated radii and lower interior temperatures associated with dynamo-generated magnetic activity (e.g. Ventura et al. 1998; Somers & Pinsonneault 2015). There is a strong (but imperfect) triple correlation between over-radius, the inverse Rossby number (an indicator of dynamo efficiency) and reduced Li depletion in our data that supports this model (see Fig. 2b). In this scenario the scatter about the correlations in Fig. 2 may reflect the stellar rotational histories, since what matters here is not the current rotation rate and radius, but what it *was* at the epoch of Li depletion, at age $\sim$ 5–30 Myr. The slow rotators with high lithium might be fast rotators that have spun down, whereas the slow rotators with low Li may always have been slow rotators. The fast rotators will always have been the fastest rotators in M35.

However, magnetic activity would probably have been "saturated" in all these stars at 5–30 Myr; it is therefore unclear whether this mechanism can imprint a strong relationship between rotation and radius at the Li depletion epoch. It seems equally possible that all these stars were inflated by similar amounts, suffered similar PMS Li depletion, but then subsequent mixing, associated with angular momentum loss and internal shear, results in *additional* Li depletion among the slower rotators (Bouvier 2008). In this scenario the fast rotators represent a baseline of Li depletion, the slow rotators with high Li would always have been slow (i.e. have spun down least), whereas the slow rotators with low Li have lost significant angular momentum, either through a primordial disc or a magnetised wind.

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