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Detection of lithium in massive stars

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Abstract. Lithium in stars more massive than $\sim 6\,M_{\odot}$ is expected to be totally depleted by the time when the stars reach the He core burning phase, as a consequence of rotationally induced mixing and other mechanisms. Some massive AGB stars present very high lithium abundances, a phenomenon explained by the activation of the Cameron-Fowler mechanism during the early thermal-pulse phase. An unexpected result of our ongoing survey of moderately young open clusters, aimed at covering stellar evolution for stars in the 6 to $10M_{\odot}$ range, is the high fraction of red (super)giants with strong Li lines. We find many more objects than expected under the assumption that the fraction of Li-rich giants is similar to that seen in the field (dominated by solar-type stars). Moreover, the stars with high lithium abundances are always the coolest and brightest in the respective clusters. Although the interpretation of these detections is not straightforward, they hint at a very early activation of the lithium production mechanism in stars in this mass range.

Key words. stars: evolution, stars: supergiants, stars: fundamental parameters, – open clusters and associations – Hertzsprung-Russell and colour-magnitude diagrams

1. Introduction

Evolved stars in open clusters are our best laboratories to carry out bench tests for theoretical evolutionary tracks. After leaving the main sequence, stars evolve towards lower effective temperatures, $T_{\rm eff}$, and become, according to their masses, red giants (RGs) or supergiants (RSGs). For initial masses higher than $4-5\ M_{\odot}$, post-MS evolution is complex (e.g. Chiosi et al. 1992; Mowlavi & Forestini 1994; Salasnich et al. 1999; Meynet & Maeder 2000). The morphological separation between RSGs (luminosity class I) and giants (III) does not reflect a strong difference in physical evolution. In fact, the most massive giants (i.e.

stars that will enter the AGB and leave behind a white dwarf as final remnant) are classified as Ib supergiants in the MK system (see, e.g., discussion in Negueruela & Marco 2012; Alonso-Santiago et al. 2019a). External appearance does not provide direct information as to whether a given star will explode as a supernova or leave behind a massive white dwarf. Modern models (e.g. Poelarends et al. 2008; Doherty et al. 2015) indicate quite high values (approaching 10 $M_\odot$) for this transition at solar metallicity, although binary interaction may have a significant effect on the final outcome. Observations of Type II SN progenitors in the Local Universe suggest that RSGs of lower masses can end their lives in an explosion (Smartt 2015).

Motivated by these questions, we started an observational programme to study young open clusters in the age range from ~30 to 100 Myr, hoping to discover observational clues of the transition from intermediate- to high-mass stars (Negueruela et al. 2017). Results of this effort are presented in Alonso-Santiago et al. (2019a) and a number of papers (see below). To our surprise, we detected a number of K-type objects with strong Li resonance lines at 6708 Å.

2. Lithium in intermediate-mass stars

Intermediate-mass stars with radiative envelopes are believed to keep their original Li abundance ($A(\mathrm{Li}) \approx 3.2$) in a thin outer layer, as mentioned in different contributions to this proceedings. During the first dredge-up, strong Li depletion reduces its abundance below $A\,(\mathrm{Li}) \leq 1.5$. The situation is nicely illustrated in clusters containing stars with masses $\lesssim 2M_\odot$ (Anthony-Twarog et al. 2018, and contributions to these proceedings). We should expect a similar evolution in more massive stars, although Li lines are not seen in stars with $T_\mathrm{eff} > 8\,500$ K (Lyubimkov 2016). Studies of low-luminosity supergiants (Luck 1977) and stars in moderately young clusters (Luck 1994) did not hint at significant differences with respect to less massive stars with radiative envelopes.

More recently, Lyubimkov et al. (2012) studied a large sample of Galactic F and G-type supergiants. From their results, they conclude that stars with initial masses $\lesssim 6M_\odot$ may show a wide range of Li abundances, ranging from non-detectable to the same value as main-sequence stars. They interpret this spread mainly as a consequence of different initial rotations. Models including the effect of rotation (e.g. Ekström et al. 2012) predict that, even for relatively low initial rotational velocities, Li is depleted below detectability by the end of the main sequence. Stars with very low rotation may keep most of their original surface Li until the first dredge-up, and a reduced abundance $A(\mathrm{Li}) \approx 1.3$ after it has happened. There are, however, a few F-type giants with quite high Li abundances, which cannot be explained with this scenario. Conversely, Lyubimkov et al. (2012) barely detect any lithium in any star with estimated mass $\gtrsim 6\ M_\odot$. According to these authors, modern stellar models predict a precipitous drop in Li abundances during the B-type giant phase for non-rotating stars of 7 to 15 $M_\odot$, and a complete depletion during the main-sequence phase for rotating stars of the same masses.

Lithium evolution does not end there. Massive AGB stars may show high Li abundances. A few such objects have been found displaying very high $A(\mathrm{Li})$ (> 3.0), while not showing high abundances of s-process elements, a combination suggestive of an evolutionary stage close to the start of the thermal-pulse phase (García-Hernández et al. 2013). In contrast, more evolved AGB stars, close to the end of the thermal-pulse phase, show high Rb abundances and a very wide range of $A(\mathrm{Li})$, a behaviour observed at different metallicities (García-Hernández et al. 2007, 2009). These observations support models that predict strong Li production at the start of the thermal-pulse phase, when Hot Bottom Burning (HBB) is activated (e.g. van Raai et al. 2012). The Cameron-Fowler mechanism (Cameron & Fowler 1971) is believed to work effectively during this phase, when the base of the envelope of an AGB star reaches $T \gtrsim 4\times10^7$ K. At these temperatures, enhanced production of ^{7}Be will occur, followed by its transportation by convection to regions of lower $T_{\rm eff}$ in the outer envelope, where it may decay into lithium (Mazzitelli et al. 1999).

3. Sample and detections

A summary of our sample selection criteria and analysis techniques is presented in Negueruela et al. (2017). Overall results have been advanced in Alonso-Santiago et al. (2019a). A detailed analysis of NGC 6067, the oldest cluster in our sample, was presented in Alonso-Santiago et al. (2017). This cluster contains 12 red bright giants or low-luminosity supergiants, one of which is likely a red straggler. We detected significant lines in three of them. Two are G-type stars that display A(Li)$\approx$ 1.2. Their position in the HR diagram is compatible with not having reached the first dredge up yet or having just undergone it. The last one is the coolest and second brightest (after the red straggler candidate) object, star 276, which presents a very high A(Li) (its properties are listed in Table 1). The cluster contains nine other objects with spectral types between G8 and K3 and two Cepheids that were observed with early-G spectral types. All of them show very weak or no Li lines.

The younger cluster NGC 2345 has been described in Alonso-Santiago et al. (2019b). Three stars with K3 – K5 Ib spectral type are observed to display strong Li resonance doublets. Their parameters are also listed in Table 1. Three other supergiants with earlier spectral types show little or no lithium. A star with similar properties has been found in the open cluster Trumpler 35, whose analysis is still unpublished.

An overall analysis of the sample presented in Negueruela et al. (2017), together with a few other clusters whose (super)giants were observed only at lower resolution, suggests that most evolved objects with masses $\sim$ 7 $M_\odot$ present spectral types in a very narrow range between G8 and K1, with luminosities Ib or II, occupying positions in HR diagrams equivalent to the red clump of lower-mass stars. None of these objects displays significant Li lines. Many clusters contain a few cooler stars. Stars with spectral types around K4 tend to have strong Li lines.

4. Discussion and conclusions

The detection of moderately large amounts of lithium in stars of 6 – 8 $M_\odot$ is at odds with the results presented by Lyubimkov et al. (2012) from their analysis of field stars, mostly of earlier spectral types. Evolutionary tracks for stars of these masses show that they may only appear as such cool objects during two moments in their evolution: a) just at the start of the He core burning, when they reach a maximum size before moving towards the blue loop or b) when leaving the blue loop and entering the AGB.

It is highly unlikely that the stars with lithium that we detect are just at the start of the He core burning phase. As commented above, modern models predict that $\approx$ 7$M_\odot$ stars should have essentially zero Li surface abundances at this stage. Moreover, when a star reaches this phase, it has already developed a very deep convective envelope, and the first dredge-up has taken place. It would thus seem that the only possible explanation for our Li-rich supergiants is an early activation of the Cameron-Fowler mechanism, as they reach the early AGB phase. Nevertheless, this explanation faces two major difficulties. For a start, models of massive AGB stars (e.g. Ventura et al. 2000) find that HBB is only activated for luminosities higher than $\log(L/L_\odot) \geq 4.3$, roughly corresponding to $M_{\rm bol} \approx -6$, significantly higher than the luminosities of our stars. Secondly, in all evolutionary tracks stars spend too little time in the early AGB phase to account for the fraction of cooler supergiants observed in our clusters. The number of stars with $T_{\rm eff} \approx 4\,000$ K (spectral types around K4) predicted by the models is negligible.

Obviously, these observational findings call for an explanation which is likely to require some revision of existing stellar models. Nevertheless, if the main theoretical prediction holds, i.e., if lithium is produced by the Cameron-Fowler mechanism, which requires HBB in an AGB star, then the presence of Li lines may be an effective discriminant between

Table 1. Lithium-rich (super)giants found in the cluster sample studied by Alonso-Santiago et al. (2019a). See this reference for further details.

Cluster	Star	Spectral type	Mass ($M_\odot$)	$M_{\rm bol}$	A(Li) (dex)
NGC 2345	14	K3 Ib	$\gtrsim 7$	−4.1	1.6
NGC 2345	50	K4 Ib	$\gtrsim 7$	−4.5	2.1
NGC 2345	1000	K4-5 Ib	$\gtrsim 7$	−4.2	1.6
NGC 6067	276	K4 II	$\lesssim 6$	−3.8	2.8
Trumpler 35	128	K4 Ib	≈ 6	−3.0	1.8

stars that enter the AGB and those that go to the supergiant phase.

We are at present exploring this possibility by extending our search for lithium to red supergiants in even younger clusters. We have recently detected strong Li lines in *Gaia* DR2 astrometric and photometric members of three poorly studied Perseus arm clusters with ages below 30 Ma. These objects have in all likelihood masses between 9 and 10 $M_\odot$. A much broader campaign is currently being organised.

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