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Strong lithium lines in red supergiants at different metallicities.

Negueruela, I.[1]**, Alonso-Santiago, J.**[2]**, Dorda, R.**[3,4] **and Patrick, L. R.**[1]

[1]Departamento de Física Aplicada, Facultad de Ciencias, Universidad de Alicante, Carretera de San Vicente s/n, E03690, San Vicente del Raspeig, Spain email: `ignacio.negueruela@ua.es`
[2] INAF–Osservatorio Astrofisico di Catania, via S. Sofia 78, 95123 Catania, Italy
[3] Instituto de Astrofísica de Canarias, Vía Láctea s/n, E38200, La Laguna, Tenerife, Spain
[4] Escuela de Arquitectura, Universidad Europea de Canarias, Tenerife, Spain

Abstract

Lithium (Li) is a fragile material, easily destroyed in stellar interiors. Within our current understanding of stellar evolution for stars more massive than $\sim 6\mathrm{M}_\odot$, Li should be depleted in the atmospheres of all such stars well before the time when they reach the He core burning phase. Despite this prediction, we find a high fraction of red supergiants (RSGs), i.e. He-core burning massive stars with convective envelopes, displaying moderate to strong Li I 6708Å doublet lines. Based on a large sample of Perseus arm RSGs, about one third of Milky Way supergiants contain measurable amounts of lithium. For the Magellanic Cloud, relatively small samples point in very different directions. In the LMC, the fraction is at least as high as that of the Milky Way. Contrarily, in the SMC, the fraction seems to be much smaller. These observational results may hint at either a Li production mechanism in RSGs or the widespread engulfment of substellar companions. Further characterisation work is ongoing, while theoretical studies into this matter are urgently needed.

1 Introduction

The light elements lithium, beryllium, and boron are important for our understanding of stellar structure because of their frailty. They are easily destroyed in stellar interiors by fusion reactions at relatively low temperatures, and thus inform us about the existence of material transport in stars. Among them, the most important isotope of lithium (^{7}Li) is the heaviest nucleus created during primordial nucleosynthesis. In the Milky Way, low-metallicity stars consistently display Li abundances around $A(\mathrm{Li}) = 2.2$ (e.g. [3]), significantly lower than predictions based on models of Big Bang nucleosynthesis. Stars with higher metallicity (Z) show higher values, around $A(\mathrm{Li}) = 3.2$, suggesting that a production mechanism exists in the present-day Universe (see [22], for a comprehensive review of light elements).

At temperatures slightly above $T = 2\times10^6$K, ^{7}Li easily captures a proton and disintegrates into two He nuclei. Therefore we expect Li to be depleted in stars with convective envelopes, unless they are very young (e.g. [14]). Intermediate-mass stars with radiative envelopes keep their original Li abundance in a thin outer layer until they leave the main sequence. Observations of clusters containing stars with masses $\lesssim 2\mathrm{M}_\odot$ show how Li is severely depleted as the star evolves, because of dilution (as the star becomes larger) and destruction in the stellar interior (e.g. [2]). More massive stars are expected to behave similarly, although Li lines cannot seen in stars with $T_{\rm eff} > 8\,500$ K ([15]). A few studies of low-luminosity supergiants [17] and stars in moderately young clusters [18] did not hint at significant differences with respect to less massive stars with radiative envelopes.

Despite this, very high Li abundances are seen in massive AGB stars, very luminous giants of late-M type, believed to represent the last phase in the life of stars with initial masses $\approx 4-9\,\mathrm{M}_\odot$. Evolved AGB stars, understood to be close to the end of the thermal-pulse phase, show high Rb abundances and a very wide range of A(Li). In the Magellanic Clouds, the brightest of such objects display $-7 \lesssim M_{\rm bol} \lesssim -6$ [12], and are believed to be stars of $\approx 7\mathrm{M}_\odot$. Other similar objects, assumed to be in a slightly earlier phase, have been found to display very high A(Li) > 3, while not showing high abundances of s-process elements [13]. Current models predict strong Li production at the start of the thermal-pulse phase, when Hot Bottom Burning is activated, as the base of the envelope of the star reaches $T \gtrsim 4 \times 10^7$ K, and the Cameron-Fowler mechanism [7] can proceed: enhanced production of beryllium (^{7}Be) will occur at the base of the envelope and convection during the third dredge-up will move it to regions of lower T in the outer layers, where it may decay into lithium [19].

The behaviour of Li in massive stars has not been studied in depth. Lyubimkov et al. [16] observed a sample of Galactic F and G-type supergiants, determining stellar parameters and Li abundances. They found that stars with initial masses $\lesssim 6\,\mathrm{M}_\odot$ may show a wide range of Li abundances, going from non-detectable to the same value as main-sequence stars, a spread that they interpret as a consequence of different initial rotations – suggesting that stars with very low rotation may keep most of their original surface Li until the first dredge-up, and a reduced abundance A(Li)$\lesssim 1.3$ after it has happened. Conversely, they barely detect any lithium in any star with estimated mass $\gtrsim 6\,\mathrm{M}_\odot$, a fact that they explain resorting to stellar models that include the effect of rotation (e.g. [4]; [10]). These models predict that, even for relatively low initial rotational velocities, Li is depleted below detectability by the end of the main sequence, due to rotational mixing. Even in models without rotation, a precipitous drop in Li abundances happens during the B-type giant phase for stars of 7 to $15\,\mathrm{M}_\odot$. The validity of these models finds some support in limited observations of the behaviour of Be, another light element [21]. Nevertheless, recent observations of red supergiants in some Milky Way open clusters have shown a non-negligible fraction of objects with strong Li lines [20, 11], in open contradiction with models and previous results. In an attempt to check if this behaviour extends to higher masses, we have observed larger samples of RSGs at different metallicities.

2 Observations

As a first step, we conducted an exploratory survey with the robotic 80 cm Telescopi Joan Oró at the Montsec Observatory. We used the ARES spectrograph with the Red VPH, which provides a resolving power $R \approx 10\,000$ over the 630 to 673 nm range. Observations, taken between December 2019 and June 2020, targeted a small sample of RSGs from the Perseus arm. Since these spectra indicated that a sizeable fraction of the RSGs present Li lines, we proceeded to observe large samples of stars.

A sample of Perseus arm RSGs was observed with the high-resolution FIbre-fed Echelle Spectrograph (FIES) attached to the 2.56 m Nordic Optical Telescope (NOT; La Palma, Spain) during a run on 2020, October 2 – 5. FIES is a cross-dispersed high-resolution echelle spectrograph that covers the 370 – 830 nm range. We used the large aperture, which provides a resolving power $R \approx 25\,000$. The spectra were homogeneously reduced using the FIEStool software in advanced mode. We observed > 50 RSGs, distributed over the Northern sky, most of them from the Cassiopeia region of the Perseus Arm. When combined with over 20 RSGs from the region of Per OB1 in [5], observed with the same instrument, this results in a sample of over 70 Perseus Arm RSGs. Sample spectra in the region of the Li I doublet are shown in Fig. 1.

Samples of RSGs at different metallicities were obtained by observing RSGs in Magellanic Cloud clusters. These objects were observed with *X-shooter*, mounted on the VLT UT3 (Melipal). Most of the observations used the UVB arm with an $1.3''$ slit ($R \approx 4\,000$) and the VIS arm with a $0.9''$ slit ($R \approx 9\,000$). Observations were obtained in service mode between 2020 October 13 and December 29. The targets observed were selected to belong to open clusters of different ages, in order to cover a wide range of masses.

3 Results

Analysis of the spectra obtained is ongoing, in order to provide a full characterisation of all the target stars that will serve as a context for the detection of Li lines. Meanwhile, visual inspection can inform us about the basic properties of the stars.

Among the Perseus Arm sample, we find a high fraction of stars with Li lines. About 25% of the stars of all spectral types (stars observed fall mainly in the K5 – M4 range, typical of Milky Way RSGs – see [9]) display strong Li lines. A few others have weak Li lines that appear blended with neighbouring weak metallic features. This result is in agreement with a recent report by [11], based on a smaller sample.

Our RSG sample in the Perseus Arm consists mostly of field stars, which cannot be assigned ages, and thus masses, to compare to evolutionary tracks. To address this issue, all our targets in the Magellanic Clouds are members of open clusters, which can provide an evolutionary context for them. Our Magellanic samples are smaller than that from the Milky Way, but likely large enough to be statistically representative. The LMC sample includes one of the most well-populated RSG clusters, NGC 2100, which is likely younger than 20 Ma, and a range of clusters extending to the well studied NGC 1755 (60 Ma), which is believed

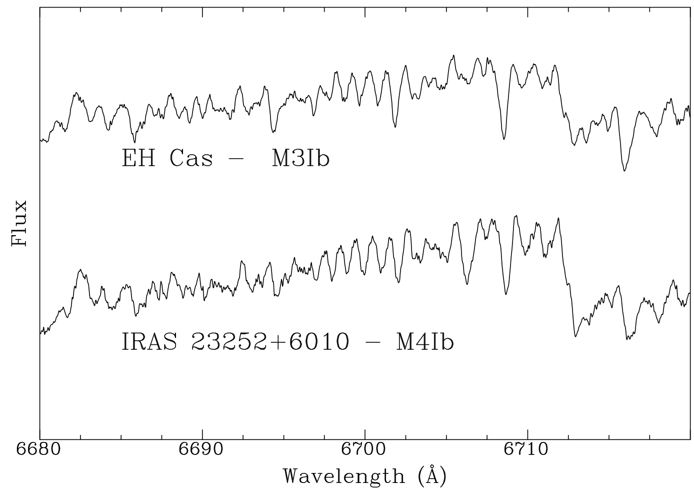

Figure 1: FIES spectra of two Perseus-arm RSGs of similar spectral type around the region where the Li I 6708 Å doublet is expected. A broad and deep Li line is seen in the spectrum of IRAS 23252+6010.

to contain RSGs of $\sim 7\,M_\odot$. In total, we have observed 21 RSGs. Stars with Li lines are found in all clusters, except in NGC 1818, where only 3 could be observed and one turns out to have an early (G) spectral type. In total, about 40% of the stars observed have lithium. Given the small sample size, this value is consistent with that found in the Milky Way.

In the SMC, the number of large young open clusters is much smaller than in the LMC, and we could not find many suitable targets. As a consequence, our clusters cover a wider range in ages, reaching NGC 256, where the RSGs are expected to have $\sim 6\,M_\odot$. Among 17 stars observed, there is only one with a moderately strong Li line, in Bruck 71. Two stars in NGC 241/2 may have weak Li present. Although the sample is small, this result very strongly suggests a different behaviour from that seen at higher Z.

4 Discussion

We find strong Li lines in a substantial fraction of RSGs in the Milky Way and the LMC. This detection is unanticipated, not only because current models for massive stars do not predict it, but also because red giants of similar spectral types do not present Li lines. Only a very small fraction of K-type giants display detectable lithium (see [24] for a comparable survey of low-mass red giants in older clusters). The lithium that we detect is unlikely to be primordial material preserved in the outer atmosphere. Irrespectively of model predictions for the atmospheric abundances of massive stars, preservation of primordial Li would require a complete absence of rotational mixing and extremely weak mass loss, both unlikely for normal stars of $\gtrsim 8\,M_\odot$.

The possibility of a production mechanism cannot be ruled out. In massive AGB stars, the Cameron-Fowler mechanism is believed to occur during the He-shell burning phase, as it relies on the penetration of the convective envelope below the H-burning shell during third dredge-up for the transport of recently created ^{7}Be to the outer regions, where it may decay to ^{7}Li that will not be destroyed because of the lower temperatures in these external layers. Some other mechanism should be at work in a true RSG, which is expected to be a He-core burning star (some lower mass stars are morphologically classified as K-type low-luminosity supergiants even if they are giants in the physical sense; a true RSG is an object classified as a supergiant that will explode as a supernova). There is an open debate at present about the possibility of a new mechanism creating Li in low mass giants (e.g. [26, 8]) and thus a different mechanism operating in massive stars is not a precluded possibility.

A second, more exotic possibility to explain the presence of Li in the atmospheres is the engulfment of substellar companions as the stars expand when crossing the Hertzsprung gap. Engulfment of giant planets has been proposed as an explanation for the existence of some Li-rich giants [1], although not considered for massive stars. However, recent observations have unveiled the presence of low-mass brown-dwarfs around early-B stars [23], making such a scenario at least worth considering. As only direct imaging can be used to search for substellar objects around hot stars, all the detections correspond to brown dwarfs orbiting their parent system at very large distances, too large to permit engulfment. Nevertheless, the existence of other brown dwarfs or giant planets at lower distances is not ruled out. Simulations suggest that a solar-type star would have its Li abundance considerably enhanced by the engulfment of a low-mass brown dwarf (e.g. [6]), but the effect on a massive star has not been studied. Recent observations suggest that some giant planets might be Li-rich [25], but the much higher fraction of RSGs with Li as compared to solar-mass giants would require some other ingredient for this mechanism to be viable.

In summary, the detection of Li in a high fraction of RSGs is extremely surprising under the light of our current stellar models. Further theoretical developments are certainly needed to provide an understanding of this phenomenon.

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