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Draco 461, an intrinsic carbon star in a metal poor stellar population: 3^{rd} dredge up and mixing

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Abstract. In July 2003 we observed the first Li-rich carbon star in a dwarf spheroidal galaxy. We compute stellar models for AGB stars and, by comparing them to the available photometric and spectroscopic data, conclude that D461 is an intrinsic carbon star, more massive and younger than the dominant stellar population of Draco.

Key words. Carbon stars – AGB stars – nucleosynthesis – dwarf spheroidal galaxies

1. Introduction

Draco 461 is a carbon star; the C enhancement may be due to the third dredge-up (TDU) that occurs in thermally pulsing AGB stars. As is well known, the TDU brings to the surface the ashes of He burning (essentially carbon) and the products of neutron capture nucleosynthesis (s-process). The detection of Tc, whose s-component has lifetime of around $2 \cdot 10^5$ yr, in galactic C(N) stars proves that they are actually undergoing the third dredge up. Nevertheless, some C-stars could not be AGB stars experiencing TDU. This may happen in interacting binary systems, when the atmosphere of the secondary (less evolved) star is polluted with the matter lost by an AGB companion (Vanture 1992; Jorissen 1999). C-stars of this type are called *extrinsic*, to be distinguished from the *intrinsic* C-stars that are AGB stars undergoing the TDU.

Current theoretical models show that there exists a minimum initial mass for the occurrence of the TDU, which varies between 1.3 and 1.5 $M_{\odot}$, depending on the metallicity and on the pre-AGB mass loss rate (see e.g. Straniero et al. 2003). This is confirmed by the observational evidence that intrinsic C-stars are not found in very old stellar systems, where stars with mass exceeding this limit have already evolved beyond the AGB.

At the average metallicity of Draco, $<$[Fe/H]$>= -2.0$ (Carney & Seitzer 1986; Bell 1985; Aparicio et al. 2001; Bellazzini et al. 2002), the minimum mass for the occurrence of the TDU cannot be lower than 1.3 $M_{\odot}$, which corresponds to an AGB age $<$ 3 Gyr. The dominant stellar population in Draco is very old, namely $\sim$ 10 Gyr (Grillmair et al. 1998). Nevertheless, the presence of anoma-

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lous Cepheids in Draco (Baade & Swope 1961; Gallart et al. 1999) demonstrates the existence of a more massive (1-2 $M_\odot$) and younger stellar population. Thus, in spite of the large age of its dominant stellar population, it is possible that some C-stars of Draco could be intrinsic AGB stars with masses of the order of 1.5 $M_\odot$ (see Domínguez et al. 2004 for details).

2. Observation and analysis

For D461 we derive $M_V = -2.74 \pm 0.14$ assuming the visual magnitude given by Shetrone et al. (2001), V=17.19, a distance modulus to Draco of $(m - M)_o = 19.84 \pm 0.14$ (Bellazzini et al. 2002) and an interstellar extinction $E(B-V) = 0.03$ (Mateo 1998).

We observed D461 with the ISIS spectrograph attached to the 4.2 m William Herschel telescope at the Roque de los Muchachos Observatory. The spectral range covered was 6450 − 8100 Å. The reduction and analysis of the individual spectra was made with the standard techniques using IRAF (for details see Domínguez et al. 2004). Our spectra confirm previous identifications of the carbon-rich nature of this star (Armandroft et al. 1995). The final spectrum has a S/N∼ 60 in the region of the Li I λ6708 Å line.

The low resolution of our spectra does not allow the detection of any unblended metal line to derive the metallicity of the star. The average metallicity of Draco, as quoted in the Introduction, is around $<$[Fe/H]$>= -2.0$ with a large dispersion, $-3.0 <$[Fe/H]< -1.5 (Shetrone et al. 1998). The lack of an IR photometry for D461 also limits the knowledge of the effective temperature of D461.

Because of these difficulties, we have computed a grid of model atmospheres for C-rich giants by means of the SAM12 program (see Pavlenko 2003 for details of this code). The following values of the model parameters have been adopted: effective temperature between 3000 and 4000 K (with a step of 200 K), C/O=1.05, 1.10, 3, 5, and 7, metallicity [Fe/H]= $-1.5, -1.7$ and -2.0, log $g = 0$ and microturbulence $\xi = 2.5$ kms^{-1}.

After an iteration process, the best reproduction of the observed spectrum of D461 has been obtained for the following values of the model atmosphere parameters: $T_{\rm eff} = 3600 \pm 200$ K, [Fe/H] $= -2.0 \pm 0.2$ and C/O between 3 and 5 (see Domínguez et al. 2004 for details). The best fit to the Li line is obtained with log ϵ(Li) $= 3.5$ with an estimated total uncertainty of ± 0.4 (mainly due to uncertainty in $T_{\rm eff}$). For ^{12}C/^{13}C only a lower limit has been obtained due to the low spectral resolution, ^{12}C/^{13}C$>$ 40. While, for s-element enhancements, we derive $+0.5 <$[Ba/Fe]$< +2.0$ from the Ba II line at λ6497 Å.

3. AGB stellar models

An evolutionary sequence of models for a star with M= 1.5 $M_\odot$, $Z = 3 \times 10^{-4}$ and Y= 0.24 have been computed using the FRANEC code (Chieffi et al. 1998). The calculation was started from the pre-main sequence up to the AGB phase. A Reimer's mass loss rate (η = 0.4) has been adopted since the RGB phase. A time-dependent mixing in the convective zones has been obtained following the algorithm described by Chieffi et al. (2001). At the convective boundaries, an exponential decay of the convective velocity is assumed, which allows the formation of a ^{13}C pocket at the epoch of the TDU (see Cristallo et al. 2004 for further details). Few thermal pulses have been followed in detail. In particular, in order to evaluate the nucleosynthesis taking places in the H and He burnings shells (s-process included), a full network of 450 isotopes (about 700 reactions) has been coupled to the stellar structure equations.

The dredge-up occurs when the inflation powered by a thermal pulse (TP) cools the base of the envelope and the H burning dies down. Starting from the second TP, the bottom of the convective envelope regularly penetrates into the H-exhausted core, down to the region previously enriched with the products of the He burning. The thermal pulse generates a convective zone that extends from the He burning shell up to the top of the H-exhausted region. Thus, C and s-process elements are efficiently mixed within this convective zone. After a dredge up episode, the expanded layers fall back, the H burning restarts and the con-

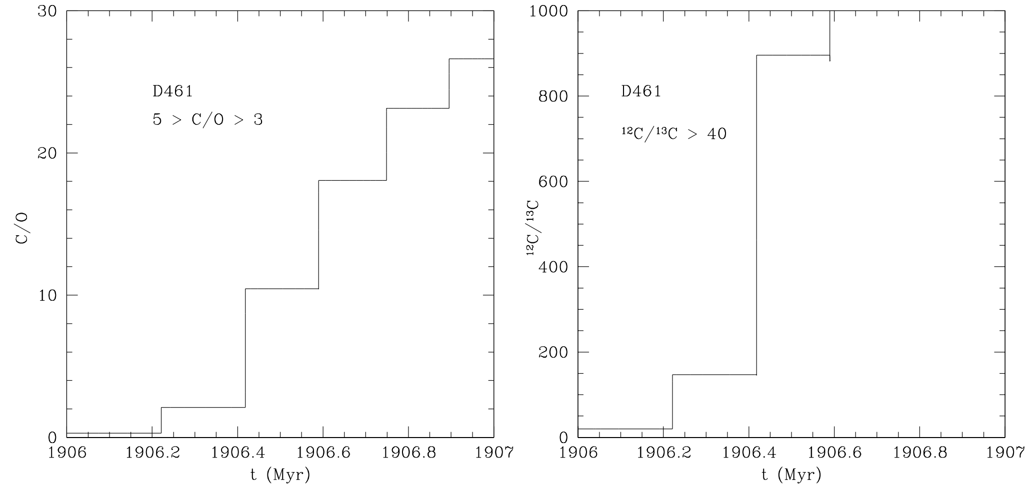

Fig. 1. Left panel: evolution with time of the surface C/O abundance (in number) along the first TPs and TDU dredge-up episodes; for D461 we derive, from the observations, a C/O ratio between 3 and 5. Right panel: same as left panel for ^{12}C/^{13}C; for D461 we derive a lower limit from the observations, ^{12}C/^{13}C> 40.

vective envelope recedes. Close to the zone of maximum penetration, the receding envelope leaves a variable profile of H. At the H reignition, a ^{13}C pocket forms in this zone. The total mass of ^{13}C within the pocket ranges between 10^{-5} $M_{\odot}$ (after the first TDU episode) and 10^{-6} $M_{\odot}$ (last computed TDU). Then, during the interpulse, the temperature rises up, until the $^{13}C(\alpha,n)^{16}O$ reaction takes place. This neutron source activates the *s*-process nucleosynthesis and then, heavy isotopes (up to Bi) are synthesized (Straniero et al. 1995; Gallino et al. 1998; Cristallo et al. 2004).

The resulting modification of the envelope composition is reported in Figures 1 and 2. Note that due to the scarcity of O in the envelope, the C/O ratio immediately grows above the unity (see Figure 1, left panel). After two dredge up episodes the C/O is about 10. Here we have assumed scaled solar initial composition. An oxygen enhancement of a factor 2 or 3, or a larger metallicity of the initial model, would lead to a better agreement with the estimated C/O ratio for D461. The lower limit for the carbon isotopic ratio and the constraint for the [Ba/Fe] are also fulfilled (see Figure 1, right panel and Figure 2, left panel). Good agreement is also found for g and $T_{\rm eff}$. The effective temperature of the models drops after the onset of the third dredge up due to the increase of the envelope opacity caused by the carbon enhancement (Marigo et al. 2002). We have simulated the change of the opacity caused by the dredge up by means of opacity tables with variable metallicity, but scaled solar mixture. This probably underestimates the contribution of some molecular species that form in a C rich mixture. Unfortunately, the available low temperature opacity tables do not include such effects.

3.1. Li production and the cool bottom process

The observed lithium abundance cannot be obtained by our standard model. This is because the temperature at the base of the convective envelope never attains 2×10^{7} K, the minimum temperature for the synthesis of Be. It is well known that a Li production may occur in AGB stars via the beryllium convective belt mechanism (Cameron & Fowler 1971). There are two

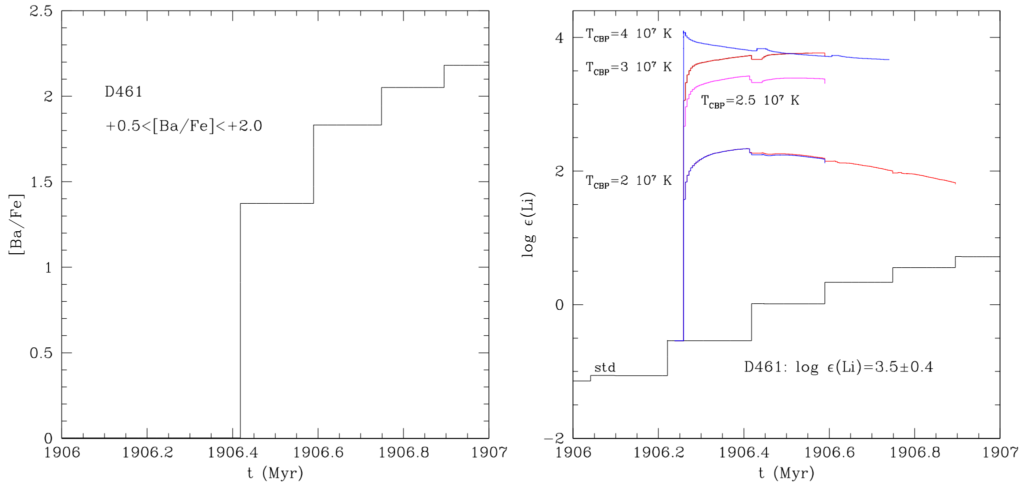

Fig. 2. Left panel: evolution with time of the surface [Ba/Fe] abundance along the first TPs and TDU episodes; for D461 we have a contraint derived from the observations, +0.5 <[Ba/Fe]< +2. Right panel: same as left panel for log ϵ(Li). Models including the CBP are characterized by the maximum temperature (T_{CBP}) reached by the circulating material, while "std" is the standar model, withouth CBP; for D461 we derive log ϵ(Li)±0.4.

conditions to be fulfilled: i) the temperature at the base of the convective envelope must be of the order of 20-30 $\times 10^6$ K, so that ^{7}Be can be produced via ^{3}He+^{4}He reaction, and ii) the mixing must be fast enough to remove the fresh Be from the hot bottom layers, before it decays into Li by electron capture. The required high temperatures are attained in massive AGB stars (Renzini & Voli 1981; Sackmann & Boothroyd 1992; Forestini & Charbonnel 1997; Lattanzio & Forestini 1999) but not in low mass AGB stars. However, there are clear indications of an efficient Li production in some low mass AGB stars.

In fact, some peculiar low mass AGB stars show low ^{12}C/^{13}C and high Li abundances, which are clear signatures of nuclear processes occurring at the base of the convective envelope (Abia & Isern 1997). To solve such kind of problems, Wasserburg et al. (1995; see also Nollet et al. 2003) suggested that some amount of material could be transported from the fully convective envelope into the underlying radiative region, down to the outer zone of the H burning shell. Although the actual physical basis for such phenomenon (that they called *cool bottom process*, CBP) is not known, it has been invoked to explain some chemical anomalies of RGB stars and in studies of dust grains that formed in circumstellar envelopes.

We have computed some additional AGB stellar models by including a parameterized description of the deep circulation during the interpluse period. Following the scheme proposed by Nollet et al. (2003), we assume that the CBP depends on two free parameters, namely the maximum temperature reached by the circulating material (T_{CBP}) and the circulation velocity (v_{CBP}). Nollet et al. actually use the mass flux instead of the circulation velocity, but these two quantities are clearly related. Note that in Nollet et al. the effect of the CBP on the nucleosynthesis was evaluated by means of a post-process code, whereas we have included this calculation in the stellar evolution code. In particular, we mimic the CBP with a deep-mixing obtained by means of the same algorithm used to describe the mixing in the convective zones (see Chieffi et al. 2001 for details). Thus, the extension and the efficiency of the deep-mixing are controlled by T_{CBP} and v_{CBP}, respectively. In agreement with the previous investigation, we find that the key parameter is the maximum temperature reached by the circulating material. T_{CBP} has been varied from 20 to 40 $\times 10^6$ K. Within this range the maximum penetration in mass is of the order of 5×10^{-3} $M_\odot$ and the physical structure of the star is very marginally affected. In the zone where the CBP takes place, we have adopted a constant circulation velocity equal to a fraction (1, 1/10, 1/100) of the mixing velocity in the most internal layers of the convective envelope. Typically the maximum explored values for v_{CBP} are of the order of 4×10^4 cm/s, which correspond to a mass flux of 0.05 $M_\odot$/yr. The minimum value is about 100 times smaller. Within this range, the resulting surface Li abundance is practically insensitive to a change of v_{CBP}.

The effect on the surface composition is illustrated in Figure 2, right panel. Models including the CBP are identified by the corresponding T_{CBP}. The standard (*std*) model refers to the case without CBP. As a consequence of the cool bottom process, the abundance of Li initially increases, reaches a maximum and then, once the ^{3}He (the fuel for the Be production) is consumed, decreases. The better agreement with the measured Li abundance in D461 is obtained for a bottom temperature of 25-30 10^6 K. Another consequence of the CBP is the partial consumption of ^{12}C and the enhancement of the ^{13}C in the envelope. This affects the carbon isotopic ratio and the C/O, which remains, in any case, within the derived observational constraints for D461.

4. Conclusions

Numerical simulations show that a thermally pulsing low mass ($\sim$ 1.5 $M_\odot$) low metallicity ([Fe/H]~ -2) AGB star undergoing the third dredge up explains all the observed features in the spectra of D461, including gravity and effective temperature. A moderate extra-mixing, like a CBP, produces Li at the observed level.

At the metallicity of Draco, the minimum mass for the occurrence of the TDU cannot be smaller than 1.3 $M_\odot$, which implies that D461 is younger than 3 Gyr. On the other hand, the observed visual magnitude (nearly that of the RGB tip) excludes the possibility that the mass of D461 could be greater than 2 $M_\odot$ which implies that D461 is older than 1 Gyr (see e.g. Table 1 in Domínguez et al. 1999).

We conclude that, although the bulk of stellar population in Draco is dominated by very old stars ($\sim$ 10 Gyr), D461 is consistent with the occurrence of star formation episodes up to 3 Gyr ago.

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