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Letter to the Editor

Fluorine in carbon-enhanced metal-poor stars: a binary scenario

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ABSTRACT

Aims. A super-solar fluorine abundance was observed in the carbon-enhanced metal-poor (CEMP) star HE 1305+0132 ([F/Fe] = +2.90, [Fe/H] = −2.5). We propose that this observation can be explained using a binary model that involve mass transfer from an asymptotic giant branch (AGB) star companion and, based on this model, we predict F abundances in CEMP stars in general. We discuss wether F can be used to discriminate between the formation histories of most CEMP stars: via binary mass transfer or from the ejecta of fast-rotating massive stars.

Methods. We compute AGB yields using different stellar evolution and nucleosynthesis codes to evaluate stellar model uncertainties. We use a simple dilution model to determine the factor by which the AGB yields should be diluted to match the abundances observed in HE 1305+0132. We further employ a binary population synthesis tool to estimate the probability of F-rich CEMP stars.

Results. The abundances observed in HE 1305+0132 can be explained if this star accreted 3−11% of the mass lost by its former AGB companion. The primary AGB star should have dredged-up at least 0.2 $M_\odot$ of material from its He-rich region into the convective envelope via third dredge-up, which corresponds to AGB models of $Z \simeq 0.0001$ and mass $\simeq 2\,M_\odot$. Many AGB model uncertainties, such as the treatment of convective borders and mass loss, require further investigation. We find that in the binary scenario most CEMP stars should also be FEMP stars, that is, have [F/Fe] > +1, while fast-rotating massive stars do not appear to produce fluorine. We conclude that fluorine is a signature of low-mass AGB pollution in CEMP stars, together with elements associated with the *slow* neutron-capture process.

Key words. stars: individual: HE 1305+0132 – stars: AGB and post-AGB – stars: abundances – nuclear reactions, nucleosynthesis, abundances

1. Introduction

Carbon-enhanced metal-poor (CEMP) stars are chemically peculiar objects, which represent 10−20% of all halo stars (Beers & Christlieb 2005; Cohen et al. 2005; Lucatello et al. 2006). Most of CEMP stars exhibit radial velocity variations, which imply the presence of a binary companion (Lucatello et al. 2005). A significant fraction of CEMP stars (∼70−80%, according to Aoki et al. 2007, CEMP-s) also exhibit enhancements in heavy elements such as Ba and Pb, which are produced by *slow* neutron captures (*s* process) in asymptotic giant branch (AGB) stars (e.g., Gallino et al. 1998). One scenario to explain the abundance patterns in CEMP stars is therefore mass transfer from a former AGB companion in which the carbon and heavy neutron-capture elements were produced (e.g., Ivans et al. 2005; Thompson et al. 2008). However, a certain fraction of CEMP stars, which have typically [Fe/H][1] < −2.7, exhibit low or no neutron-capture element abundances (CEMP-no). These stars might have formed instead from material ejected by rapidly rotating massive stars (Meynet et al. 2006) or faint type II supernovae (Umeda & Nomoto 2005). At extremely low metallicities, [Fe/H] < −4, giant CEMP stars could have enriched themselves in carbon via a "dual core flash" – where mixing of protons during the core helium flash induces a hydrogen flash – while in the early phases of AGB stars of masses ≤1.5 $M_\odot$ and [Fe/H] ≤ −2.3, a "dual shell flash" may occur, where protons are ingested into the convective pulse (Fujimoto et al. 1990; Hollowell et al. 1990; Fujimoto et al. 2000; Picardi et al. 2004; Cristallo et al. 2007).

⋆ The first two authors have contributed equally to this paper.

[1] $[X/Y] = \log(X/X_\odot) - \log(Y/Y_\odot)$.

Schuler et al. (2007) derived a super-solar fluorine abundance of $A(\mathrm{F})$[2] = +4.96 ± 0.21 for the halo star HE 1305+0132, which corresponds to [F/Fe] = +2.9. This is the most Fe-deficient star, [Fe/H] = −2.5 ± 0.5, for which the fluorine abundance has been measured to date. HE 1305+0132 also exhibits overabundances of C and N ([C/Fe] = +2.68 ± 0.51; [N/Fe] = +1.6 ± 0.46) and an O abundance typical of halo stars ([O/Fe] = +0.50 ± 0.22). Lines of Ba and Sr are observed in its spectra (Goswami 2005), which place HE 1305+0132 in the group of CEMP-s stars.

Fluorine abundances were first determined in AGB stars by Jorissen et al. (1992). Enhancements of up to 30 times the solar value were reported, demonstrating that these stars produce fluorine. Observations of post-AGB stars and planetary nebulae, the progeny of AGB stars, confirm that these objects are also enriched in fluorine (Werner et al. 2005; Zhang & Liu 2005). type II supernovae (Woosley & Haxton 1988) and Wolf-Rayet stars during helium burning (Meynet & Arnould 2000) have been theoretically identified as F production sites, but they are not observationally confirmed. In contrast to that observed in CEMP stars and in particular HE 1305+0132, type II supernovae typically produce more O than C, a part from a narrow range of initial mass around 80 $M_\odot$ (Woosley et al. 2002) or in the case of faint supernovae at $Z = 0$ (Umeda & Nomoto 2005), while models of Wolf-Rayet stars show that fluorine production in these stars scales with stellar metallicity and decreases when rapid rotation is included (Palacios et al. 2005).

The aims of this paper are to discuss the yields of C, N, and F from AGB stars at the metallicities relevant to CEMP stars (Sect. 2); to determine if the abundances measured for HE 1305+0132 can be explained using the AGB binary scenario (Sect. 3); and to evaluate the consequences of fluorine production in AGB stars on the CEMP stellar population (Sect. 4). We evaluate AGB modelling uncertainties related to different physics prescriptions and nuclear reaction rates in Sect. 5 and present our conclusions in Sect. 6.

2. C, N, and F from low metallicity AGB stars

Fluorine can be produced in AGB stars via the $^{18}\mathrm{O}(\mathrm{p},\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ reaction chain during thermal pulses (TPs) associated with the periodic activation of the He-burning shell. While ^{18}O is provided by the $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+}\nu)^{18}\mathrm{O}$ chain, protons are produced via $^{14}\mathrm{N}(\mathrm{n,p})^{14}\mathrm{C}$ reactions, and neutrons originate from $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ reactions. The ^{13}C and ^{14}N nuclei are mixed down into the convective He shell from the ashes of the H-burning shell. After each TP quenches, third dredge-up (TDU) may occur, which trasports ^{19}F to the convective envelope, together with ^{12}C produced by partial He burning in the TPs.

Yields for C, N, and F at [Fe/H] = −2.3 from the models of Lugaro et al. (2004) and Karakas & Lattanzio (2007) are shown in Fig. 1. The reader is referred to these papers for details of the computational methods. The profiles of the C and the F yields as a function of the initial stellar mass closely follow each other. This is because the TDU carries primary ^{12}C to the stellar envelope. This is converted into primary ^{13}C and ^{14}N in the H-burning ashes, whose abundances drive the synthesis of F. Hence, fluorine production in AGB stars of low metallicity is of a primary nature (Lugaro et al. 2004). When the stellar mass is higher than ≃3 $M_\odot$, proton captures at the base of the convective envelope (hot bottom burning, HBB) lead to the conversion of C into N and to the destruction of F. Hence, we expect that the high F abundance ([F/Fe] ≈ +4) predicted by Meynet et al. (2006) in the envelope of a low-metallicity rotating 7 $M_\odot$ model at the beginning of the AGB phase will be completely destroyed by HBB during the subsequent AGB phase.

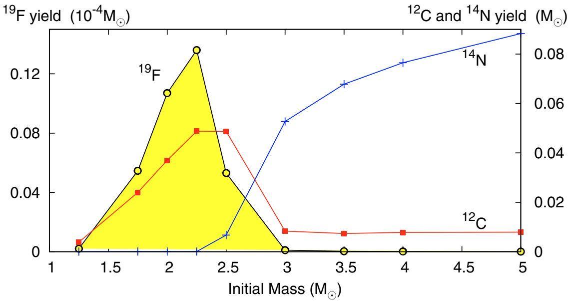

Fig. 1. C, N, and F yields from AGB models of different masses and [Fe/H] = −2.3. Note that the F yields are plotted on a different scale.

Since the $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio in HE 1305+0132 is observed close to its equilibrium value (Goswami 2005) and N is mildly enhanced, proton captures may have occurred inside this star, or in the AGB companion, due to non-convective-mixing processes that occurr below the inner boundary of the convective envelope. These can be due, for example, to efficient activation of thermohaline mixing (Charbonnel & Zahn 2007). An alternative explanation may be the occurrence of the dual shell flash in the AGB star. The high observed F abundance indicates that F cannot have been significantly destroyed by proton captures via the $^{19}\mathrm{F}(\mathrm{p},\alpha)^{16}\mathrm{O}$ reaction, thus constraining the temperature reached by any extra mixing process to less than ≃20 million degrees, within reaction rate uncertainties (see, e.g, Figs. 2 and 3 of Arnould et al. 1999).

3. Estimate of binary transfer parameters

In Fig. 2 we show the abundances of F and C+N[3], relative to H, observed in the star and compare these values to the abundance ratios in the material lost by AGB stars according to the models presented in Fig. 1. To reproduce the observed abundances we employ two free parameters: (1) the initial mass of the polluting AGB star, which determines the chemical composition of the accreted material; and (2) the amount by which the accreted material is diluted into the envelope of the polluted star. In Fig. 2 the composition that is produced by the mixing of material before accretion with material from the AGB star lies on a straight line connecting the two components; the amount of dilution is represented by the position of the point on the mixing line. To explain the measured abundances, we require an AGB initial mass of between 1.7 and 2.3 $M_\odot$, and dilution of the accreted material by a factor of between six and nine.

If we assume that the mass of HE 1305+0132 is 0.8 $M_\odot$, which is the typical mass of halo stars, and calculate the evolutionary track of a star of this mass and metallicity $Z = 10^{-4}$ (using the stellar evolution code STARS, see, e.g., Pols et al. 1995), we find that the observed effective temperature T = 4.46 ± 0.10 kK (Schuler et al. 2007) indicates that the star is a giant with a convective envelope. When the envelope reaches its maximum depth, the outermost 60% of the mass of the star is

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[2] $A(\mathrm{Element}) = \log N(\mathrm{Element}) + 12$.

[3] We prefer to use C+N rather than C because our models do not take into account the possibility that some C is converted into N.

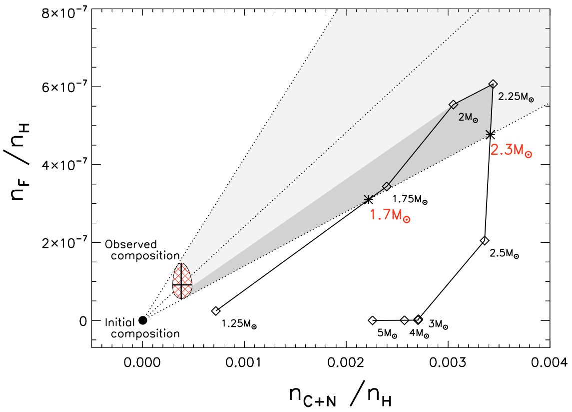

Fig. 2. Abundances by number of F and C+N with respect to H as observed in HE 1305+0132 with 1σ errors, taken from Schuler et al. (2007, hatched ellipsoid), and computed in the average material lost via the winds by AGB stars at [Fe/H] = −2.3, with labels indicating the initial masses. The initial composition is scaled from solar. The gray area is the region of the plot where the F and C+N abundances from the AGB companion should lie to ensure that the observed abundances are reproduced after dilution. The darker gray area represents the region covered by our models with masses in the range indicated by the asterisks.

convective[4] With these assumptions, we find that the star should have accreted 0.05−0.12 $M_\odot$ from a former AGB companion. Given that the total mass lost during AGB evolution is in the range 1.0−1.5 $M_\odot$, this corresponds to the accretion of 3−11% of the mass lost by the AGB star.

We implicitly assume that the composition of the accreted material can be represented well by the average composition of the total material ejected by the AGB star. In reality, however, the binary orbit is altered during mass transfer, so the composition of the accreted material varies because the surface AGB composition varies. Moreover, the evolution of the AGB star itself may be altered by the presence of a binary companion. Since there are no models presently available that describe both binary and detailed AGB evolution simultaneously, we have defaulted to using the AGB average composition.

In principle, it is possible to constrain the initial orbital period of the binary system. The system must have been sufficiently wide to allow the primary star to evolve into an AGB star before filling its Roche lobe; this requirement sets a lower limit to the initial orbital period. On the other hand, the efficiency of wind accretion decreases with the distance between the two stars, which implies that the required amount of accreted material may set an upper limit on the initial orbital period. Using the binary evolution code described in Izzard et al. (2006), we find that the range of initial orbital periods that corresponds to an accretion efficiency >3% in a system with initial masses 0.8 and 2 $M_\odot$ is between 7 and 27 years.

4. Fluorine abundances in CEMP stars from binary systems

With the binary evolution code described in Izzard et al. (2006), we simulated a population of binaries assuming the Kroupa et al. (1993) initial mass function, a uniform distribution of initial mass ratios, and the Duquennoy & Mayor (1991) initial period distribution.

Table 1. Number of TPs with TDU, total TDU mass, and C, N, and F yields (all in $M_\odot$) for different AGB models of 2 $M_\odot$ at [Fe/H] = −2.3.

	Model	TPs	$M_{\rm TDU}$	C	N	F
1	Karakas[a]	25	0.22	3.7E-02	7.2E-05	1.1E-05
2	pocket[b]	"	"	"	"	1.7E-05
3	^{18}F(α, p) UL[b]	"	"	"	"	2.8E-05
4	pocket + UL[b]	"	"	"	"	3.3E-05
5	Cristallo[c]	14	0.09	1.7E-02	3.4E-05	2.4E-06
6	Cristallo[d]	49	0.19	3.1E-2	1.2E-4	1.1E-05

[a] Lugaro et al. (2004) and Karakas & Lattanzio (2007); [b] Karakas et al. (2008); [c] Cristallo et al. (2007); [d] Cristallo (2006).

We find that, of all turn-off and giant CEMP stars formed by mass transfer from an AGB companion, 81% are expected to show an enhanced fluorine abundance of [F/Fe] > +1, 12% have [F/Fe] > +2, and 0.005% have [F/Fe] > +3. This can be understood qualitatively from the results presented in Fig. 1 because AGB stars that produce carbon also produce fluorine. To date, fluorine enhancements have not been reported for other CEMP stars because high-resolution spectra in the 2.3−2.4 μm band are required, which are not yet available. We predict that fluorine should be found in most CEMP stars that formed via the AGB binary scenario, thus representing a tracer of low-mass AGB pollution in addition to *s*-process element enhancements.

The fluorine abundance in the particular case of HE 1305+0132 appears to be exceptionally high, since we expect only 0.04% of turn-off and giant CEMP stars to have $A(^{19}\rm F) \geq +4.75$, when considering the observational error bar. However, we emphasize that many uncertainties play a role in this estimate, both in the assumed distribution functions (which are reasonable for stars in the solar neighbourhood, but not necessarily for halo stars), and in the assumed wind accretion efficiency. The latter is based on the Bondi & Hoyle (1944) prescription, whereas hydrodynamical simulations (Theuns et al. 1996; Nagae et al. 2004) predict typically lower accretion efficiencies. These uncertainties deserve more attention in a follow-up study (Izzard et al., in preparation). Moreover, the theoretical understanding of F production in AGB stars is itself still affected by many uncertainties, as discussed below.

5. Uncertainties in AGB models

To evaluate AGB model uncertainties we discuss a set of models of 2 $M_\odot$ and [Fe/H] = −2.3, computed using different physics and nuclear reaction rate assumptions (Table 1). The first four models in Table 1 are computed using the codes described in Karakas & Lattanzio (2007). Model 1 is that used in the previous section for comparison with HE 1305+0132. Model 2 includes a region in which protons from the envelope are mixed down into the top layer of the He- and C-rich intershell (the region between the H and He shells) at the end of each TDU. Proton captures on ^{12}C generate a "pocket" rich in ^{13}C, the main neutron source for the *s*-process in these stars, and ^{14}N (Herwig 2005). Extra ^{15}N is produced in the ^{13}C-^{14}N pocket, which is then converted to ^{19}F in the following convective TP (see also Goriely & Mowlavi 2000). The introduction of a ^{13}C-^{14}N pocket of 0.002 $M_\odot$ increases the ^{19}F yield by 60%, while the C and N yields are unaffected. In Model 3 of Table 1 we consider a model computed using the upper limit (UL) of the ^{18}F(α, p)^{21}Ne rate. This increases the ^{19}F yield by a factor of ≃2.5 (see details

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[4] The mixed fraction might be as much as 90% if thermohaline mixing is effective (Stancliffe et al. 2007), even though this may be debated in particular regarding the possible counter-effect of gravitational settling (see, e.g., Thompson et al. 2008; Aoki et al. 2008).

and discussion in Karakas et al. 2008). When both a ^{13}C-^{14}N pocket and the upper limit of the ^{18}F$(\alpha, \mathrm{p})^{21}$Ne reaction rate is used (Model 4 of Table 1), the ^{19}F yield increases by a factor of three. The other main nuclear uncertainties originate from the ^{14}C$(\alpha, \gamma)^{18}$O and the ^{19}F$(\alpha, \mathrm{p})^{22}$Ne reaction rates (see discussion in Lugaro et al. 2004). For the latter, the latest evaluation by Ugalde et al. (2008) needs to be tested in AGB models.

All models presented do not take account of the effects induced by carbon enhancement on the opacities of the cool external layers of AGB stars. When $\mathrm{C/O} > 1$, C-bearing molecules, most notably $\mathrm{C_2}$ and CN, increase the opacity of the external layers, causing the envelope to expand and the star to become larger and cooler (Marigo 2002). Models of AGB stars of low mass and metallicity with C- and N-enhanced low-temperature opacities have been calculated using the Frascati Raphson Newton evolutionary code (FRANEC) code (Straniero et al. 2006; Cristallo et al. 2007). In these models the mass-loss rate strongly increases with respect to models in which opacities are always calculated using the initial $Z = 10^{-4}$ solar-scaled composition. The resulting yields (Model 5 of Table 1) are ≈5 times smaller than in the Karakas models. For comparison, the results obtained with the same code, but using opacities calculated for the initial solar-scaled composition (Cristallo 2006) are also reported in Table 1 (Model 6), and are in good agreement with the Karakas model, in spite of the different choices of mass-loss rate and treatment of the convective borders (see Straniero et al. 2006, for details).

It is evident that further work is required to address the uncertainties in the AGB fluorine yields at low metallicities. In particular, the inclusion of low-temperature carbon-enhanced opacities in the Karakas models (Karakas et al., in preparation) will provide an independent comparison to the results obtained by the FRANEC code and by Marigo (2002). Since a clear dependence of the mass-loss rate on the metallicity has still not be identified, different mass-loss prescriptions should be tested (Cristallo et al., in preparation). Finally, we note that the possible occurrence of the dual shell flash at the beginning of the AGB phase may also affect fluorine production and needs to be investigated in detail (e.g, Campbell & Lattanzio 2008).

6. Discussion and conclusions

We have shown that it is possible to reproduce the C and F abundances observed in the CEMP-s star HE 1305+0132 via binary mass transfer from a companion by accretion of 3−11% of the mass lost by the primary star during its AGB phase. The AGB star should have dredged-up at least $\simeq 0.2\,M_\odot$ of its intershell material into the convective envelope by means of the TDU. While rapidly rotating massive stars produce enough carbon and nitrogen to form CEMP stars, they do not appear to produce fluorine (Palacios et al. 2005). The binary formation scenario is thus favoured in the case of HE 1305+0132. In general, we predict that most CEMP stars formed by mass transfer from an AGB companion should also be FEMP stars, i.e., have $[\mathrm{F/Fe}] > +1$. Hence, fluorine appears to be a useful discriminant between the different scenarios proposed for the formation of CEMP stars.

During the preparation of this manuscript, another halo object highly enriched in fluorine was discovered, the planetary nebula BoBn 1 (Otsuka et al. 2008). The metallicity, as well as all the C and N abundances observed in this object are the same, within errors, as those of HE 1305+0132, which suggests that BoBn 1 has a close connection to CEMP stars, perhaps representing the evolutionary outcome of a CEMP star. On the other hand, the derived F abundance in this object is roughly a factor of three higher than that obtained for HE 1305+0132. This observation can be explained via the binary scenario only if we consider the F yields we computed including the ^{13}C-^{14}N pocket or the upper limit of the ^{18}F$(\alpha, \mathrm{p})^{21}$Ne reaction. Following this indication, we multiplied the F yields by a factor of three in our stellar population model and calculated a probability of 12% for CEMP stars to have $A(^{19}\mathrm{F}) \geq +4.75$. This result provides us with a possibility to alleviate the problem of the extremely small probability of the high F abundance assessed for HE 1305+0132.

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