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Nucleosynthesis Origin of PG 1159 Stars, Sakurai's Object, and Rare Subclasses of Presolar Grains

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Abstract. We discuss theoretical AGB-stage predictions for the hydrogen-deficient PG 1159 stars and Sakurai's object, which show peculiar enhancements in He, C, and O, and how these enhancements may be understood in the framework of a very late thermal pulse nucleosynthetic event. We then discuss the nucleosynthesis origin of rare subclasses of presolar grains extracted from carbonaceous meteorites, the SiC AB grains showing low $^{12}C/^{13}C$ ratios in the range 2 to 10 and the very rare high-density graphite grains with $^{12}C/^{13}C$ around 10.

1. H–Deficient Stars

1.1. PG 1159 Stars: Extremely Hot Post-AGB Stars

The hydrogen-deficiency in extremely hot post-AGB stars of spectral class PG 1159, which includes about 40 stars with $T_{\rm eff}$ ranging from 75 000 and 200 000 K and log g from 5.5 to 7.5, is probably caused by a very late thermal pulse (VLTP) in the He shell (Schönberner 1979; Iben 1984) while the post-AGB star is on the hot white-dwarf (WD) cooling sequence. Because of the high $T_{\rm eff}$ in PG 1159 stars, all species are highly ionized and, hence, most metals are only accessible by UV spectroscopy. A passionate investigation has been conducted in the last 20 years by Klaus Werner and collaborators (Werner & Herwig 2006; Werner et al. 2009, 2010, and references therein). In Table 1 we report in particular the range of peculiar abundances of He, C, N, and O estimated in PG 1159 stars, where the mass fraction of He ranges between 0.30 and 0.85, of C between 0.15 and 0.40, of N between 0.001 and 0.01, and of O between 0.02 and 0.2. The energy released by the VLTP forces the stellar radius to inflate and the star to cool and proceed back toward a born-again AGB star. At the maximum extension of the convective thermal instability the very small residual and inactivated H shell is likely engulfed by the pulse and severely depleted, so that the usually hidden He-rich, C-rich, and *s*-element-rich He intershell is eventually exposed to the photosphere.

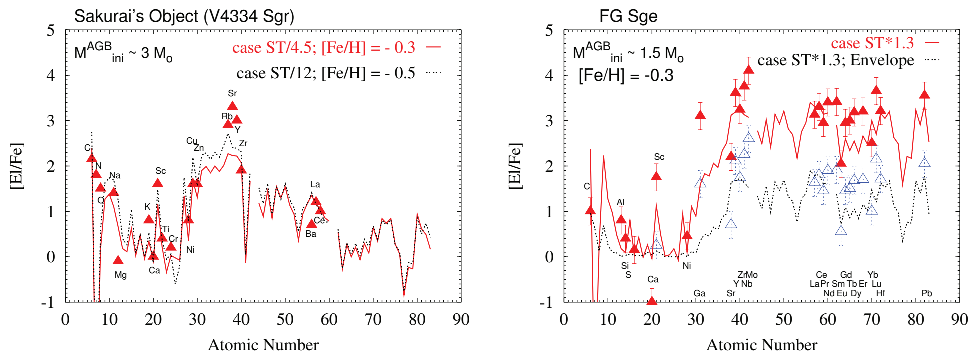

Figure 1. *Left*: Sakurai's object. Spectroscopic data by Asplund et al. (1998) compared with the [El/Fe] distribution in the He intershell for different AGB models of M_{ini}^{AGB} = 3 M$_\odot$, [Fe/H] = −0.3, case ST/4.5 at the last thermal pulse, and for [Fe/H] = −0.5 and case ST/12. *Right*: FG Sge. Spectroscopic data by Gonzalez et al. (1998) compared with an AGB model of M_{ini}^{AGB} = 1.5 M$_\odot$, [Fe/H] = −0.3, case ST × 1.3 at the last thermal pulse. The lower curve is for the distribution in the envelope at the last thermal pulse for the same AGB model (see text).

PG 1159 stars are seemingly descendants of [WC] stars, which show similar HeCNO peculiarities.

1.2. Sakurai's Object (V4334 Sgr)

Sakurai's object (V4334 Sgr) was discovered in 1996 and was soon recognized to be the central star of an old planetary nebula (6000 yr old). It recently underwent a VLTP and is now a hydrogen-deficient born-again AGB star. The estimated mass fractions He/C/O = 0.90/0.07/0.03 and other element abundances (Asplund et al. 1998, their Figure 6) are reported in Table 1 and compared with PG1159 stars. This composition is based on the choice of the best adopted atmospheric model with C/He ≈ 0.10 (by number). Note that there is a "carbon problem" for Sakurai's object similar to that encountered for the hydrogen-deficient R CrB stars. Indeed, the spectroscopic C abundance derived from C I lines is about 0.6 dex smaller than the one deduced from the selected model atmosphere. The same is the case for [Fe/H]. However, the relative abundance ratios [El/Fe] are scarcely dependent on the choice of C/He ratio. In Figure 1 (left) we compare the observed [El/Fe] data of Sakurai's object with predicted abundances in the He intershell at the last thermal pulse for an AGB model of M_{ini}^{AGB} = 3 M$_\odot$, [Fe/H] = −0.3, case ST/4.5. Given the uncertainty of the initial metallicity, we also plot in the figure a similar predicted [El/Fe] distribution for M_{ini}^{AGB} = 3 M$_\odot$, [Fe/H] = −0.5 and case ST/12 (dashed line). In this case, Sc and Rb appear better reproduced, but the reverse is true for C and Cu. As to Sr, its abundance in October 1996 was overestimated. The presence of carbon dust buffers around Sakurai's object may in general introduce a noticeable uncertainty in spectroscopic abundances. V605 Aql (Nova Aql 1919) is a second star having likely suffered a VLTP about 90 yr ago. Clayton et al. (2006) estimated He/C/O = 0.54/0.40/0.05. Both V106 Aql and Sakurai's object showed peculiar rapid declines and fading characteristic of episodic carbon dust emission, as in the case of R CrB stars. However, as discussed below, several R CrB stars likely originated in a completely different way, as binary WD mergers.

1.3. H Ingestion and Partial Burning in the He Intershell

In order to produce a consistent amount of N and to achieve the low $^{12}C/^{13}C$ value observed in Sakurai's object, ingestion and burning of hydrogen in a TP is impossible when the H shell is still active. It may work when a very thin H envelope is left after the star leaves the AGB (Herwig et al. 1999; Miller Bertolami et al. 2006). A quite low $^{12}C/^{13}C \leq 10$ results while a consistent amount of ^{14}N is built up. During the AGB phase, standard elemental mass fractions in the He intershell after a thermal pulse are He/C/O = 0.75/0.20/0.005. Higher C and O abundances may be obtained by including an efficient overshoot at the base of the convective thermal pulse in the TP-AGB phase (Herwig et al. 1997). Alternatively, proper account should be given to the peeling effect by mass loss both at the tip of the AGB and in the early phase of the post-AGB track. There, a "superwind" of up to several 10^{-5} $M_\odot$/yr has been measured. Lawlor & MacDonald (2006) introduced these effects in their stellar evolution code in a wide spectrum of initial masses and metallicities. Another important factor is the thickness of the He buffer, which decreases with increasing CO core mass, i.e. with the initial stellar mass. The authors showed that chemical peculiarities observed in stars having suffered the VLTP do not strictly require overshoot in the AGB phase. One should also consider that the bottom of the VLTP is degenerate, different from what occurs during the AGB phase, with the possibility of further increasing C and O.

Table 1. Composition of PG 1159 stars and Sakurai's object, AGB He-intershell predictions, and extra needs. The spectroscopic data for Sakurai's object are from Asplund et al. (1998, their Fig. 6). Our AGB predictions for Ne refer to ^{22}Ne, the most abundant isotope in the He intershell. The range of ^{19}F for AGB He-intershell predictions increases with the number of thermal pulses, i.e. with the initial AGB mass.

	PG 1159	Sakurai's object	He intershell	extra needs
$^{12}C/^{13}C$	not measurable	2 to 5	NO ^{13}C	H-b
H	deficient	deficient	0.	
He	0.30 to 0.85	0.90	0.75	partial He-b
C	0.15 to 0.60	0.07	0.2	partial He-b
N	0.001 to 0.01	0.01	0.	H-b
O	0.02 to 0.20	0.03	0.005	partial He-b
F	1 to 250 × solar	not detectable	1 to 250	
Ne	0.02	0.02	0.02	
Na		25 × solar	8 × solar	
Si	solar to 0.5 × solar	7 × solar	solar	
S	solar to 0.1 × solar	2.5 × solar	solar	
P	solar to 2 × solar		1–4 × solar	
Ar	solar		solar	
Fe	solar to 0.1 × solar	0.6 × solar	0.7–1 × solar	
Ni	not enhanced	8 × solar	not enhanced	
Cu		55 × solar	25 × solar	
Zn		55 × solar	20 × solar	
s-elem.	impossible to detect	highly enhanced	highly enhanced	

1.4. FG Sge

The peculiar variable FG Sge has also been assumed to have recently suffered a VLTP. Over the last 120 years FG Sge evolved from a hot post-AGB star to a present cool and born-again AGB star. Figure 1 (right) shows the FG Sge spectroscopic data by Gonzalez et al. (1998) (full triangles) compared with theoretical predictions (upper curve) in the He-intershell after the last thermal pulse for an AGB initial mass of 1.5 $M_\odot$, metallicity [Fe/H] = −0.3 and the ^{13}C pocket choice ST × 1.3. Note the huge [ls/Fe], [hs/Fe] and [Pb/Fe], on the order of 3 dex each. The high value [Eu/Fe] = 2 dex observed is *s*-process Eu, in agreement with the typical *s*-process expectation $[La/Fe]_s \approx$ 1 dex. Moreover, Gonzalez et al. estimated $^{12}C/^{13}C > 10$ and provided the first spectroscopic evidence of H-deficiency. Jeffery & Schönberner (2006) reanalyzed all extant spectroscopic data and atmospheric parameters, raising doubts as to the huge *s*-process abundances derived by Gonzalez et al. (1998). The lower $T_{\rm eff}$ = 5500 K chosen for the model atmosphere led Jeffery & Schönberner to conclude that the *s*-process element abundances are more than one order of magnitude less than inferred, most likely inherited already from its previous AGB phase. They concluded that FG Sge suffered a late thermal pulse (LTP), not a VLTP, then evolved back to a born-again AGB star. In the lower curve of Figure 1, we compare the envelope AGB model prediction at the last thermal pulse. Note that the two indicators of the *s*-process distribution, [hs/ls] and [Pb/hs], would remain unaltered. The spectroscopic heavy elements have been reduced by 1.5 dex (open triangles), which corresponds to a typical factor of 30 dilution of He intershell material mixed with the envelope. Note that the predicted [C/Fe] value would better compare with a LTP solution.

1.5. The R CrB Stars

So far about 50 R CrB stars have been discovered. Their atmospheres are extremely hydrogen deficient and carbon rich. Another distinctive feature of some R CrB stars is the enormous F abundance, in the range 1,000 to 8,000 times solar for [Fe/H] in the range −0.5 to −2.0 (Pandey, Lambert, & Rao 2008). Such drastic ^{18}O and ^{19}F excesses indicate that the merging of a CO–WD with a He–WD gives rise to partial He burning and production of ^{18}O via α-capture on ^{14}N, accompanied by $^{18}O(p,\gamma)^{19}F$. Detailed nucleosynthesis calculations for these peculiar objects are not easy, however.

2. Presolar Grains

A subclass of presolar SiC grains discovered in carbonaceus meteorites, the SiC grains of type AB (4 to 5 % of all presolar SiC grains) are characterized by very low $^{12}C/^{13}C$ ratios, in the range 2 to 10. Mainstream SiC grains (covering 93% of all presolar SiC grains), show higher $^{12}C/^{13}C$ ratios, from ∼10 to 100 (the solar ratio is 89), averaging around 60 (Zinner 1998, 2008). While mainstream SiC grains likely originated in low-mass AGB stars of around solar metallicity, the stellar origin of SiC AB grains is still enigmatic. These grains clearly show the signature of H burning in the CNO cycle, and H burning is also indicated by their relatively high inferred $^{26}Al/^{27}Al$ ratios (Amari et al. 2001). However, the low $^{12}C/^{13}C$ ratios are difficult to reconcile with the condition C > O, necessary for SiC condensation. J-type carbon stars and born-again AGB stars like Sakurai's object have been proposed as sources of AB grains. Despite SiC AB grains showing low $^{12}C/^{13}C$, the permil variations of $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ with respect

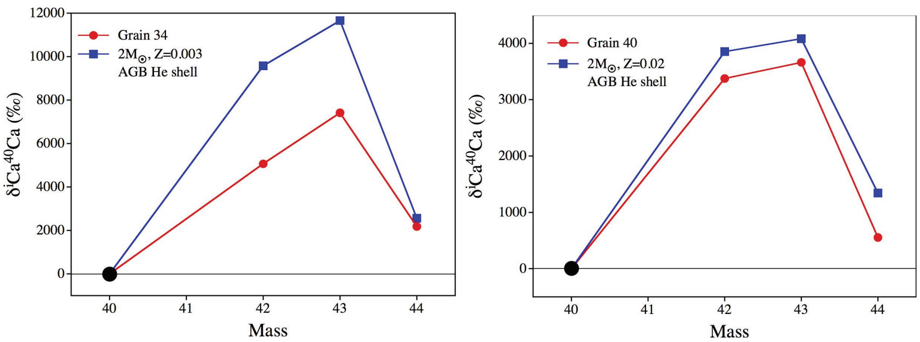

Figure 2. Permil variation with respect to solar of Ca isotopes of graphite presolar grains g-34 and g-40 compared with He intershell predictions of two different AGB models (adapted from Jadhav et al. 2008).

to solar are indistinguishable from mainstream SiC that reach maximum values of ~200 and ~150, respectively. Instead, far higher permil variations are predicted in the He intershell. This indicates that SiC AB grains are incompatible with an origin in born-again AGB stars like Sakurai's object, unless one speculates that the grains formed in a cool circumstellar disk, after having been mixed with previously ejected material.

Very rare high-density graphite grains have been discovered with the signature of the He intershell in the trace elements Ca and Ti (Jadhav et al. 2008). Two examples are reported in the two panels of Figure 2, for the grains g-34 and g-40. A similar exceptional permil variation has been detected for both Ca and Ti in grain g-9. Also trace Mg and Si are present but they show essentially normal isotopic composition, perhaps related to isotopic equilibration with solar material.

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