Triple-alpha burning products on the surface of peculiar post-AGB stars

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Abstract. The so-called PG 1159 stars form a new spectroscopic class of extremely hot hydrogen-deficient post-AGB stars. Our spectral analyses with model atmospheres show that their chemical surface composition is dominated by carbon, helium, and oxygen. We suggest that these peculiar stars have suffered a late helium-shell flash which has caused the removal of the hydrogen-rich envelope and even most of the helium-rich intershell matter. The idea that the former helium-burning region is now exposed at the surface of the PG 1159 stars is supported by the recent detection of a very high amount of neon in some objects.

The most extreme object is H 1504+65 which is one of the brightest X-ray sources in the sky and the hottest star ever analyzed with model atmosphere techniques ($T_{\rm eff}$=170 000 K). The photosphere is devoid of hydrogen **and** helium and composed of oxygen and carbon by equal amounts! This means that we look at the naked core of the former Red Giant. This gives us the unique possibility to confine empirically the still uncertainly known ^{12}C$(\alpha,\gamma)^{16}$O nuclear reaction rate.

Key words: Stellar Atmospheres — ^{12}C$(\alpha,\gamma)^{16}$O reaction rate.

1. PG 1159 stars

The PG 1159 stars currently comprise 22 known objects. They are very hot hydrogen-deficient post-AGB stars characterized by their unusual spectral appearance. They display broad and shallow absorption lines of He II and C IV and occasionally O VI. Most prominent is an absorption trough region made up by He II 4686Å and a blend of several C IV lines. Eleven members of this group are associated with old extended planetary nebulae (PNe) and it is speculated that the other objects lack a visible PN because they have dispersed in the interstellar medium. Seven PG 1159 stars were shown to be non-radial g-mode pulsators. In particular the prototype star (PG 1159−035) has been studied photometrically with outstanding scrutiny by the Whole Earth Telescope project (Winget et al. 1991). These stars are primary examples demonstrating the power of the recently developed asteroseismological tools to study the interior structure of stars.

Analyses of high-S/N medium-resolution spectra obtained at telescopes of the 3-meter class in Chile (ESO) and Spain (Calar Alto) were performed with non-LTE model stellar atmospheres. The nine objects examined so far span a wide range of effective temperatures, from 65 000 K up to 170 000 K. The surface gravities are high, ranging from $\log g = 5.9$ (cgs units) for the luminous central stars to $\log g = 8.0$ for the most evolved object. The surface composition is generally dominated by carbon and helium in roughly equal amounts (by mass) and high admixtures (up to 17%) of oxygen. Comparison with stellar evolutionary tracks gives masses typical for white dwarfs (about 0.6 $M_\odot$), with the two extreme values 0.5 and 0.87 $M_\odot$. The luminosities range from about 10 to 10^4 $L_\odot$ and the distances are between 0.5 and 3 kiloparsec (for a recent review see Werner 1993).

The chemical surface abundances indicate that the PG 1159 stars have lost their hydrogen-rich envelope and even most of the helium-rich intershell region almost down to the carbon-oxygen-rich core. This is supported by pulsational models which predict that non-radial pulsations are driven by the kappa-effect involving carbon and oxygen. High amounts of C and O (roughly 80%) are required for this mechanism, a low amount of helium (at most about 20%) and no hydrogen at all may be present. Most recent results indicate indeed that the helium layer in PG 1159−035 is thinned down (from about $10^{-2} M_\odot$) by a factor of 5 (Kawaler & Bradley 1994). As far as accessible by both, spectroscopic and pulsational analysis methods, the derived stellar parameters (effective temperature, mass, surface composition) are in excellent agreement in the best studied case, PG 1159−035.

2. Evolutionary state

What is the evolutionary history of the PG 1159 stars? The answer to this question is still open. One possible interpretation of the peculiar chemical abundances is that the PG 1159 stars are the result of a late helium-shell flash in the precursor star. Such an event may happen to a post-AGB star that has almost contracted to white dwarf dimensions. As a consequence the star re-expands to giant dimensions ("born-again AGB star") and retraces the post-AGB evolution for the second time. During this course the star might strip off its envelope layers down to layers where triple-alpha burning has taken place. The recent detection of high amounts of neon (20 times solar) in some PG 1159 stars supports this idea (Werner & Rauch 1994). Neon is strongly enhanced in the helium burning shell by the reaction $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta,\nu)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$. This chain starts with ^{14}N which was produced previously during CNO burning.

Detailed evolutionary calculations are lacking for this highly dynamic phenomenon of a late helium flash, therefore other explanations (like mixing and burning of the surface hydrogen) cannot be ruled out at the moment.

Immediate precursors of the PG 1159 stars may be identified with the Wolf-Rayet central stars of PNe, more exactly with the early type [WC] stars (i.e. spectral type [WCE]). This is based on the abundance analyses of the [WC 2] central star NGC 6751 (Hamann & Koesterke 1993) as well as two transition objects (classified as [WC]–PG 1159), the well known central stars of A 30 and A 78 (Werner & Koesterke 1992, Leuenhagen et al. 1993), which are PNe with strongly H-deficient knots expelled from the central stars. These stars show abundance patterns similar to the PG 1159 class. A very strong confirmation of the [WC]–PG 1159 evolutionary link represents the observation of a mass-loss event in the central star of Longmore 4 which turned its spectral type from PG 1159 to [WC] and back within a few weeks (Werner et al. 1992).

PG 1159 stars should evolve into hot helium-rich (DO) white dwarfs as soon as steadily increasing gravitational forces remove the heavy elements (C and O) from the atmospheres. A prerequisite is that the stars have not retained traces of hydrogen in the envelope which would eventually float atop and turn the star into a hydrogen-rich (DA) white dwarf. At this point we emphasize that the upper limits of the hydrogen abundance from the spectroscopic analyes are not very strict. A fraction of 10% would easily escape detection. Such an amount is certainly enough to turn the star into a DA. If the envelope "peeling" scenario for the PG 1159s is right, however, then we can in fact assume that their fate is to become a DO. But caution is necessary and this is underlined by the detection of the hybrid central stars (objects with high He and C abundances *and* detectable hydrogen).

In any case, the existence of DO white dwarfs makes at least a subgroup of the PG 1159 stars likely progenitors (although doubt is cast even on this statement by two known central stars with almost pure helium atmospheres, namely K1-27 and LoTr 4 [Rauch et al. 1994a,b]). About a dozen hot DO white dwarfs (defined by the absence of He I lines) are known at present and detailed non-LTE model atmosphere analyses are now becoming available. KPD 0005+5106 was studied in the optical, UV and X-ray regions and found to be extremely hot (T_{eff}=120 000 K).

3. H 1504+65 and the ^{12}C$(\alpha,\gamma)^{16}$O nuclear reaction rate

The most extreme PG 1159 star is H 1504+65. It is not only the hottest star ever analyzed with model atmosphere techniques (T_{eff}=170000 K) but it has a photosphere that is hydrogen *and* helium-deficient (Werner 1991). Thus the atmosphere is solely composed of carbon and oxygen. We have interpreted this composition as the exposition of the naked C-O stellar core of the former Red Giant. Thus we are in the advantageous situation to constrain empirically the ^{12}C$(\alpha,\gamma)^{16}$O nuclear reaction rate because we directly see the immediate burning product.

The knowledge of this reaction rate is still scarce but it is of high astrophysical interest for many reasons. Time scales of late stages of massive star evolution and the position in the HR diagram depend sensitively on the adopted value for this rate. Additionally the carbon and oxygen enrichment in the interstellar medium during the course of galactic chemical evolution depends on yields of stellar evolution calculations which in turn depend on the ^{12}C$(\alpha,\gamma)^{16}$O nuclear reaction rate. The internal composition of C-O white dwarfs and through this the cooling time scales are essentially depending on this rate, too. The rate proposed by Fowler et al. (1975) (F) has been increased by Harris et al. (1983) by a factor of three ($F \cdot 3$). Subsequently the rate was decreased again down to $F \cdot 2$ by Caughlan & Fowler (1988).

Constraining the rate from our C/O abundance ratio determination is not straightforward for several reasons. Besides the error bars of our analysis (O= $50 \pm 20\%$, by mass) uncertainties in stellar evolution calculations, particularly concerning mixing processes, render a conclusive result difficult.

According to evolutionary calculations by Iben & Tutukov (1985) for a model with a mass appropriate for H 1504+65 and adopting a $F \cdot 2$ rate, we may expect an oxygen abundance of 40%. Following calculations of D'Antona & Mazzitelli (1991) we may estimate that a change of the $^{12}C(\alpha,\gamma)^{16}O$ rate to F or $F \cdot 3$ roughly results in O abundances of 30% and 50%, respectively. We therefore conclude that a rate as high as $F \cdot 3$ agrees best with our observations. This result agrees e.g. with the analysis of ejecta from the supernova 1987A (Thielemann et al. 1990).

Currently we work on the improvement of our photospheric analysis. Important tools are the ROSAT, Hubble Space Telescope (HST) and Extreme Ultraviolet Explorer (EUVE) satellites. X-ray, UV and EUV spectra of H 1504+65 were already obtained and are now being examined in detail (Barstow et al. 1994). The results are expected to further constrain our estimates for the $^{12}C(\alpha,\gamma)^{16}O$ nuclear reaction rate.

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