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ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

Third-dredge-up oxygen in planetary nebulae *

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Abstract. The planetary nebulae He 2-436 and Wray 16-423 in the Sagittarius dwarf galaxy appear to result from nearly twin stars, except that third-dredge-up carbon is more abundant in He 2-436. A thorough photoionization-model analysis implies that ratios Ne/O, S/O and Ar/O are significantly smaller in He 2-436, indicative of third-dredge-up oxygen enrichment. The enrichment of oxygen with respect to carbon is (7±4)%. Excess nitrogen in Wray 16-423 suggests third dredge-up of late-CN-cycle products even in these low-mass, intermediate-metallicity stars.

Key words: Nuclear reactions, nucleosynthesis, abundances - (ISM:) planetary nebulae: general - (ISM:) planetary nebulae: individual: He 2-436 and Wray 16-423 - Galaxies: dwarf - Galaxies: individual: Sagittarius

1. Introduction

It is usually assumed (*e.g.* Henry 1989) that the oxygen abundance of a planetary nebula (PN) reflects the metallicity Z of the interstellar medium (ISM) in which the parent star formed, inasmuch as the conversion of ^{16}O into ^{14}N due to advanced CNO processing is unimportant, a condition fulfilled in low-mass stars ($M < 2\ M_{\odot}$). Low-mass stars bring to their surface nitrogen (through first dredge-up), produced by CN-cycle conversion of carbon, and carbon (third dredge-up), produced by 3-α fusion along the Asymptotic Giant Branch (AGB, *e.g.* Iben & Renzini 1983). During He-burning, ^{14}N is transformed notably into ^{22}Ne and some ^{12}C into ^{16}O. Thus third dredge-up is likely to bring freshly synthesized oxygen to the surface of low-mass stars, as suggested by Boothroyd & Sackmann (1988, here BS88) and, in a preliminary form, by Herwig et al. (2000, here HBD), who invoked intershell dredge-up ("fourth dredge-up", Iben 1999) by diffusive overshoot. Exposed deep layers of hydrogen-deficient post-AGB stars appear to have quite similar concentrations of oxygen and carbon (Koesterke & Hamann 1997; Herwig et al. 1999) but *the amount of fresh oxygen expelled from AGB stars is unknown.* The oxygen abundance is difficult to determine in the atmosphere of evolved stars (*e.g.* Fulbright & Kraft 1999) and shows large scatter in PNe of a given galaxy (*e.g.* Leisy & Dennefeld 1996, here LD96).

In order to reveal the oxygen enrichment of PNe, one must seek for circumstances enabling the detection of a small excess of oxygen. Two PNe, He 2-436 and Wray 16-423, were found (Zijlstra & Walsh 1996, here ZW96; Walsh et al. 1997) to belong to the Sagittarius dwarf galaxy (Ibata et al. 1995). Spatial and kinematic properties point to a common origin for these PNe. Photoionization models (Dudziak et al. 2000, here DPZW) indicate nearly identical depletions with respect to solar for all elements beyond nitrogen [(-0.55 ± 0.07) dex]. Both PN nuclei are early-type [WC] stars belonging to nearly the same (H-burning) evolutionary track M=$(1.2 \pm 0.1)M_{\odot}$, Z=0.004 (Vassiliadis & Wood 1994), consistent with their precursors being the intermediate-age carbon stars of Sagittarius. As expected, third dredge-up yield was large in these intermediate-Z stars (Marigo et al. 1999), but even larger in He 2-436. If both stars were born in the same star formation episode with identical abundances, advantage can be taken of their low initial abundances and different third-dredge-up yields to study the influence of this process upon oxygen and other elements by comparison of the respective abundances. Here, unlike the general study of DPZW, emphasis is on abundance *ratios* and differential effects. Péquignot et al. (2000) gave a preliminary account.

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* Based on observations collected at ESO La Silla, Chile.

2. The Sagittarius dwarf galaxy PN models

Spectra of Wray 16-423 and He 2-436 were secured in identical conditions. Their small apparent size led to global spectra of the highest reproducibility and relevance for modeling. The many theoretical line ratios (H I, He I, forbidden multiplets) allowed to check that statistical errors on measured fluxes were realistic, the few discrepancies being indeed similar in both PNe. Thus, in a direct comparison, systematic errors are likely to cancel out.

In the photoionization model analysis of DPZW, the error bars attached to the abundances of these PNe were estimated from comparing two independent codes: they represented, at some "1σ level", the uncertainties left after evaluating the origin of the differences between codes and trying to include systematic errors. Here, only one of the photoionization codes (code NEBU; *e.g.* Morisset & Péquignot 1996) is used, considering only the statistical error on line fluxes. Because of the neglect of systematic errors, the intervals are much reduced. Conversely, because of the "plasticity" allowed by the rather large number of free parameters and the thorough exploration of all possible solutions, the intervals can be enlarged. The abundance *ratios*, which were not considered in the error analysis of DPZW, are determined with greater accuracy than the individual abundances, as shown below.

Current [WC]-atmosphere models are not reliable: in order not to miss solutions because of restrictive assumptions, black-body stars with a discontinuity at the He^+ limit were employed as a three-parameter sequence and an equivalence was established with the NLTE model stellar atmosphere (effective temperature $T_{\rm eff}$), from the grid of Clegg & Middlemass (1987). Similar free-parameter sets, procedures and convergence criteria were adopted to obtain two-sector models for both PNe. The models matched essentially all line fluxes within 1σ errors, that is no more than a few percent of line strength for most basic lines. The two discrepancies left, one of them involving [O I] and the other one [Ar IV]/[Ar III], turned out to be identical for both PNe, suggesting systematic effects.

It was possible to generate several models of each PN satisfying the very strong and numerous observational constraints, as three key line fluxes (C II 426.7, [O II] 372.6 and [S II] 406.8*nm*) were not very accurately determined. Given a $T_{\rm eff}$ for the central star, the model parameters are constrained by imaging and/or radio continuum data and by (accurate) optical line fluxes. A noticeable aspect is the global energy balance. The cooling rate, mainly determined by the unknown C III] and C IV UV line fluxes (in addition to [O III]), depends on the carbon abundance, to which C II is proportional. For Wray 16-423, the computed C II flux is always in agreement with observation, stronger limitations being brought by other lines. For He 2-436, considering different models with increasing density in the dense sector (an incomplete inner shell), both the [O III]500.7*nm*/[O III]436.3*nm* ratio and the [O III]500.7*nm* flux tend to decrease, but can be reconciled with observation by increasing the oxygen and carbon abundances. As free parameters ensure sufficient flexibility, the uniqueness of the solution breaks down and the boundaries of the set of acceptable models (and abundances) are now determined by the C II flux.

In Fig. 1 are shown for both PNe the ranges of allowed carbon and oxygen abundances versus the $T_{\rm eff}$'s. Varying $T_{\rm eff}$ makes the predicted [S II] 406.8*nm* and [O II] 372.6*nm* fluxes vary relative to other lines in models. For He 2-436, low or high $T_{\rm eff}$'s are forbidden as the [S II] or [O II] fluxes become too large. Relaxing somewhat the error bars attached to these lines increases the allowed range of $T_{\rm eff}$ without much changing the range of acceptable abundances. As for Wray 16-423, all elements but carbon have abundances virtually independent of $T_{\rm eff}$. Low $T_{\rm eff}$'s (low C abundances) are forbidden by two independent [S II] lines being predicted too weak; high $T_{\rm eff}$'s by one accurately observed [S II] line becoming too large. Higher $T_{\rm eff}$'s are also excluded by the fact the He^+ discontinuity, constrained by He II 468.6*nm*, would be much larger than in atmosphere models. Also the shape of the model nebula would then deviate from observation.

The oxygen abundances of the He 2-436 models encompass the well defined value of Wray 16-423. Nevertheless oxygen *tends* to be larger in He 2-436. As a check of this tendency, Wray 16-423 models were run with the oxygen abundance increased by 10%. No satisfactory solution could be found. Re-convergence on all parameters was performed until all lines except [O III] 500.7*nm* and [O III] 436.3*nm* were again satisfactory and the discrepancy on both [O III] line fluxes was reduced to a minimum, typically 5σ. Other elemental abundances increased by 9 ± 1% (except C: 18%). An He 2-436 model of given $T_{\rm eff}$ was then re-converged to a solution, though with the condition that the computed [O III] line fluxes should reproduce the discrepancy met in the previous Wray 16-423 model. In this new He 2-436 model, most abundances were shifted upwards relative to the standard solution by 8 ± 1% (except N: 3% and C: 18%), close to the shift imposed on oxygen in the Wray 16-423 model. This numerical experiment suggests that systematic errors may substantially shift the derived abundances but not influence conclusions based on differences between the two PN models.

Table 1 lists the absolute helium and oxygen abundances by number and other abundances relative to oxygen. For all elements but carbon, the quoted abundance "uncertainty" is obtained by adding linearly the full abundance spread of acceptable models to the 1σ error of the best determined line (the models were constrained to reproduce this line exactly). Percent differences on abundance ratios and 1σ error bars (Table 1, col. 4) clearly show that Ne/O, S/O and Ar/O are smaller in He 2-436 than in Wray 16-423 (3.5, 1.8 and 1.4σ confidence levels respectively, hence 4.2σ collectively). Given that sulfur and argon are not synthesized in low-mass stars and that neon

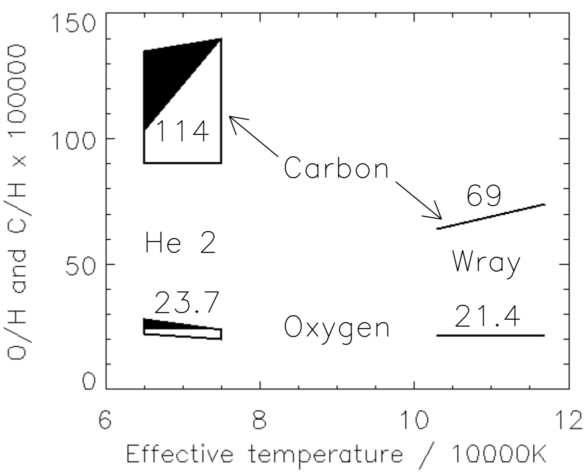

Fig. 1. Acceptable abundances of C and O by number versus $T_{\rm eff}$ of central stars according to model nebulae for He 2-436 and Wray 16-423. Best-model values are indicated. The shaded areas correspond to He 2-436 models having the same sulfur abundance as Wray 16-423 within uncertainties (Sect. 3). For $T_{\rm eff}/10^4$K = 6.5, $10^5\times$O/H increases from 24 to 28 as $10^5\times$C/H increases from 104 to 135. For $T_{\rm eff}/10^4$K = 7.5, the O and C values are 24 and 140 respectively.

Table 1. Abundance ratios by number in Sagittarius PNe

Ratio	Wray 16-423	He 2-436	diff. (%)
He/H	0.108±0.002	0.108±0.003	0.0±3.6
O/H	(21.4±0.2)$\times10^{-5}$	(24.0±4.0)$\times10^{-5}$	–11.5±16.
C/O	3.22±0.23	5.0±0.8	–43.3±17.
N/O	0.213±0.015	0.116±0.006	59.0±8.7
Ne/O	0.168±0.003	0.147±0.005	13.3±3.8
S/O	0.0201±0.0008	0.0162±0.0016	24.0±13.
Ar/O	0.0042±0.0004	0.0029±0.0007	36.6±26.

should hardly be affected either, *this very significant trend must be due to a larger oxygen abundance in He 2-436.* An explanation involving an abundance fluctuation in the ISM with, *e.g.*, an excess *specific* to oxygen at the birth place of the parent star of He 2-436 is unlikely, as these stars are twins in most respects (ZW96, DPZW) *and* the Ne/O ratio is remarkably stable, at $\sim$ 0.18, in the ISM of even different galaxies (*e.g.* Henry 1989). Thus the most plausible interpretation of the excess is in terms of *oxygen production*, with the precursor star of He 2-436 having been more efficient than that of Wray 16-423. Since He 2-436 shows a larger carbon excess – the signature of third dredge-up – it is inferred that this process was also able to bring freshly synthesized oxygen to the star surface.

Table 2. Evolution of abundances* in stellar envelopes

Stage: Elmt	Init	1st drge-up + CBP[a]	3rd drge-up (Wray)	3rd drge-up (He 2)
He	8250	9000	10800±200	10800±300
O	(17)	16.5±3.2	21.4±0.2	26.0±2.0
C	4	2.5	69.±5.	122.±18.
N	1	2.5	4.6±0.3	3.0±0.3
Ne	-	3.4	3.59±0.07	3.8±0.3
S	-	0.43	0.43±0.02	0.43±0.02
Ar	-	0.08	0.09±0.01	0.07±0.02

*Abundances by number in units H = 10^5
[a]Cool Bottom Processing (Boothroyd & Sackmann 1999)

3. Discussion

In Table 2 is sketched a possible evolution of the stellar envelope composition, assuming that (1) initial compositions were identical in the Wray 16-423 and He 2-436 stars, (2) sulfur abundance was constant, keeping the value determined for Wray 16-423 within uncertainties (col. 4 of Table 2), and (3) oxygen abundance varied linearly with that of carbon during third dredge-up (cols. 4, 5). Sulfur is preferred to argon as a reference constant-abundance element, in view of the moderate scatter of the sulfur abundance determinations in models and the difficulty met in accounting for the argon ionization (DPZW). Scatter is less for neon, but its nucleogenic status may be less clear-cut and the variation of Ne/O from Wray 16-423 to He 2-436, although significant, is smaller. Reliable sulfur abundances are difficult to obtain in PNe, yet this approach is justified considering that models are based on homogeneous procedures and used only in a differential manner.

Once the sulfur abundance is specified for He 2-436, the range of possible oxygen abundances is narrowed: assuming the errors are independent, S/O (Table 1, col. 3) and S (Table 2, col. 4) imply $23.6 < 10^5\times$(O/H) < 28, an interval that excludes the O/H value of Wray 16-423. Owing to the linear increase of S with O in the model results, the minimum O/H is in fact slightly larger (Table 2, col. 5; Fig. 1, shaded areas). Let ΔO and ΔC be the increments by number of the oxygen and carbon abundances due to third dredge-up. Taking into account correlations between C and O in He 2-436 models (Fig. 1: the lowest C goes with the lowest O) and assumption (3) above, the difference in abundances between the two PNe shows that extreme values for ΔO/ΔC are 2.4/76=0.03 and 6.8/61=0.11.

The extrapolated main-sequence abundance of oxygen (Table 2, col. 3 or 2), obtained assuming carbon is initially much less abundant than in the PNe, is used only to determine Z and relevant initial abundances (see below).

The present result for ΔO/ΔC seems to fit with old predictions of BS88 for flash-produced intershell O/C in the region mixed after convection but this may be fortuitous: these stellar models are uncertain, as indicated by Herwig (2000) who obtained models for intermediate-mass high-Z stars using an exponential diffusive overshoot formalism. Based on the same concept, HBD obtained preliminary models for low-Z stars, suggesting that surface O/C reaches asymptotically the intershell value, $\sim 1/3$. Thus, considering tendencies shown by recent star models, the present coarse estimate would seem to imply that *relatively little oxygen* should be third-dredged-up. Nonetheless a PN is formed after many ejection episodes and its abundance may be far from reflecting asymptotic values.

By contrast, neon and argon appear constant within uncertainties and the lower abundance of nitrogen in He 2-436 cannot be due to extensive conversion of this element into heavier ones. The initial (Table 2, col. 2) and first-dredge-up (col. 3) helium, carbon and nitrogen abundances are from Boothroyd & Sackmann (1999) assuming M=1.2 $M_\odot$ and Z=0.004 (in keeping with extrapolated oxygen). Second dredge-up does not occur in low-mass stars, but these authors take into account deep-circulation mixing leading to enhanced $^{13}C/^{12}C$, as observed along the red giant branch, and to further conversion of initial carbon into nitrogen. This so-called "Cool Bottom Processing", sensitive to Z and M, can bring the nitrogen abundance quite close to that of He 2-436 but perhaps not to the larger one of Wray 16-423 (Table 2). Another source of nitrogen is required.

Mixing of ^1H with fresh ^{12}C occurs in low-mass AGB stars to produce ^{13}C, s-nuclei *etc*, but the hydrodynamics involved is not understood (Lattanzio & Frost 1997). It may not be excluded that some ^{13}C can find its way up to the hydrogen shell or that insertion of H-rich pockets into the He/C-rich intershell is, on occasion, efficient enough to allow CN-cycle completion. In this way, low-mass AGB stars could synthesize some ^{14}N from fresh ^{12}C and mimic intermediate-mass stars in which the so-called "Hot Bottom Burning", together with third dredge-up, is believed to lead to (N-rich) Type I PNe. Within the uncertainties of the definition (Torres-Peimbert & Peimbert 1997), Wray 16-423 would in fact be marginally Type I in the Large Magellanic Cloud (LMC). The indication here is that *the dredge-up of additional nitrogen was more effective in Wray 16-423, where carbon is less overabundant*.

According to BS88, the He/C ratio in the carbon pockets that will be dredged-up levels off rapidly at He/C ~ 8 by number, compatible with the "observed" third-dredge-up ΔHe/ΔC, which lies anywhere between 15 and -15 (Table 2, cols. 4, 5), but not with the large jump of helium between first dredge-up and Wray 16-423. This may suggest, among other possibilities, that the initial helium abundance adopted here for these stars was too small.

Abundances are comparable in the PNe of Sagittarius and LMC (LD96). The abundance scatter in the LMC is likely due to the coexistence of several populations, but Ne/O is expected to be relatively stable, except possibly for differential effects of the kind revealed here. ¿From data of LD96, it is found that log(Ne/O) is –0.61±0.10 and –0.83±0.10 for Type-I and non-Type-I PNe respectively. These determinations bracket the mean H II-region value, –0.74 (see LD96), and appear marginally different. Assuming that neon best traces the overall LMC evolution, this suggests that oxygen is relatively depleted in Type I, at least as a consequence of second dredge-up in intermediate-mass stars (see also Dopita & Meatheringham, 1991), but *enhanced* in non-Type I by third dredge-up in accord with present finding in Sagittarius PNe.

Abundances are lower in the SMC than in the LMC. Nitrogen-rich PNe of the SMC (type i+I of LD96) are found among extremely low Z stars, presumably of low initial mass. Also some halo PNe have N/O > 1 (Howard et al. 1997), at variance with the well-known association of Type I PNe with intermediate-mass stars, but maybe another manifestation of what is occuring in Sagittarius: *^{14}N is enhanced by third dredge-up in low-mass AGB stars* and, due to a combination of efficiency and titration effect, N/O can reach large values for sufficiently small Z.

The discussion of the Sagittarius PN models (DPZW) makes it clear that improvement of the critical carbon abundance can be expected from more complete observations (UV, far red). Nevertheless the present results can already provide some constraints on the new generation of models for the evolution of low-mass low-Z stars and lead to a re-interpretation of trends shown by PN abundances in low-Z environments. The production of oxygen by low-mass stars ($\sim 2\times10^{-4} M_\odot$/star in Sagittarius) may have to be considered in galactic-evolution models.

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