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THIRD-DREDGE-UP OXYGEN IN PLANETARY NEBULAE?

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RESUMEN

Las dos nebulosas planetarias (PNe) Wray 16–423 y He 2–436 pertenecen a la recientemente encontrada galaxia enana de Sagitario y parecieran ser eventos casi gemelos. El carbono es más abundante en He 2–436, confirmando que la cantidad de material del tercer dragado puede ser diferente en objetos que de otra manera son similares. La alta homgeneidad de los datos obtenidos y de los procedimientos usados, el origen común de estas PNe, sus altas aunque diferentes sobreabundancias de C y las bajas abundancias iniciales de las estrellas progenitoras, ofrecen circunstancias favorables para el estudio de los subproductos del tercer dragado. El modelaje con fotoionización indica muy fuertemente que, suponiendo abundancias idénticas de azufre, el oxígeno es más abundante en He 2–436 que en Wray 16–423, quizás mostrando por primera vez el oxígeno del tercer dragado. Si el C está principalmente en forma gaseosa, dentro de un factor de dos, el incremento del cociente por número es $\Delta O/\Delta C = 0.07$. El argón se mantiene casi constante mientras que el neón se incrementa ligeramente junto con el C y el O. Queda sin resolver la relación entre el exceso de nitrógeno y la menor sobreabundancia de C en Wray 16–423.

ABSTRACT

The two planetary nebulae (PNe) Wray 16–423 and He 2–436 belong to the newly recognized Sagittarius dwarf galaxy and appear as nearly twin events. Carbon is more abundant in He 2–436, confirming that the amount of third-dredge-up material may be different in two otherwise similar objects. The high degree of homogeneity of all available data sets and adopted procedures, the common origin of these PNe, their large and different C overabundances, and finally the low initial abundances of their parent stars provide favorable circumstances to study by-products of the third dredge-up. Extensive photoionization modeling strongly suggests that, assuming identical sulfur abundances, oxygen is more abundant in He 2–436 than in Wray 16–423, thus possibly disclosing for the first time third-dredge-up oxygen. If C is mainly in gaseous form, the increment ratio by number is $\Delta O/\Delta C = 0.07$ within a factor of 2. Argon is roughly constant whereas neon may moderately increase together with C and O. An open question is the relationship between the excess of nitrogen and the lesser overabundance of C in Wray 16–423.

Key Words: **GALAXIES: DWARF — ISM: ABUNDANCES — PLANETARY NEBULAE: INDIVIDUAL (HE 2-436, WRAY 16-423) — STARS: AGB AND POST-AGB**

1. INTRODUCTION

It is now widely accepted that the parent stars of planetary nebulae (PNe), the stars with initial mass $1 < M/M_\odot < 8$, play a key role in the synthesis of helium, carbon, nitrogen and s-process elements.

On the other hand, the synthesis of oxygen and neon is passed on to massive stars. It is usual to assume that the oxygen abundance of a PN reflects the abundance of the interstellar medium at the time its parent

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star was born, at least for low-mass stars ($M < 2.5\ M_\odot$) in which the conversion of O into N due to advanced CNO processing is unimportant. These stars bring to their surface some nitrogen (1st dredge-up) produced by CN-cycle conversion of carbon, and copious amounts of carbon (3rd dredge-up) produced by 3-α fusion. In 3-α burning conditions, the N from the CN cycle can be transformed into Ne and heavier elements, while a poorly known fraction of ^{12}C can be transformed into ^{16}O. In parallel, complex hydrodynamic processes make some fresh ^{12}C to mix with ^{1}H, then producing ^{13}C which, on reacting with ^{4}He, ends up as ^{16}O and free neutrons responsible for the synthesis of s-process nuclei. It is thus not excluded that 3rd dredge-up may bring some freshly synthesized oxygen to the surface of low-mass stars.

Nitrogen and/or carbon enrichment is often prominent in PNe, leaving no doubt that large fractions of these elements were synthesized in the parent star. This may not be the case for oxygen and one must seek for circumstances enabling the detection of a small relative enrichment.

2. THE SAGITTARIUS DWARF GALAXY PLANETARY NEBULAE

Two PNe, He 2–436 and Wray 16–423, were found (Zijlstra & Walsh 1996) to belong to the newly recognized Sagittarius dwarf galaxy. Optical spectroscopy, radio continuum measurements and photoionization modeling (Walsh et al. 1997; Dudziak et al. 2000) indicated that these PNe have a common origin, both showing nearly identical depletions with respect to solar for all elements beyond nitrogen [(-0.55 ± 0.07) dex] and both belonging to nearly the same (H-burning) evolutionary track [(1.3 ± 0.1) $M_\odot$], compatible with the carbon stars of this galaxy being their Asymptotic Giant Branch precursors. Wray 16–423 was modeled as an ellipsoidal nebula, with a 15% radiation-bounded, denser sector, excited by a star of effective temperature 1.07×10^5K, and He 2–436 as a double-shell nebula with a high-density, radiation-bounded, incomplete inner shell and an outer lower-density region, excited by an 0.70×10^5K star. The small mass and time-scale of this inner shell imply a transitory event, presumably related to a late thermal pulse. Both the stellar evolution timescales and the gas distributions/kinematics of the nebulae confirm that these PNe are twin events with Wray 16–423 having occured $\sim$ 2500 years before He 2–436.

Third dredge-up was very active, as expected for low-metallicity low-mass stars, and more efficient in He 2–436. This difference is not unexpected as the total amount of 3rd-dredge-up material depends sensitively on the timing of the last thermal pulse(s). An excess of N present in Wray 16–423 is more intriguing (see below).

We now consider a tendency for oxygen to appear slightly more abundant in He 2–436 than in Wray 16–423. So far, the confidence intervals associated with the abundances overlapped but they resulted from comparing two independent codes and included likely systematic effects (Dudziak et al. 2000). In fact, the spectra of these PNe were secured and reduced simultaneously by the same people using the same instruments and procedures. The small apparent size of the PNe led to global spectra of the highest reproducibility and relevance for modeling. Also, we restricted ourselves to the more elaborate models obtained with one of the photoionization codes (Péquignot et al., in preparation), the same people applying similar procedures and convergence criteria to obtain two-sector models in all cases. Comparing the results differentially, systematic errors are then likely to cancel out, the uncertainties arising mainly from statistical errors on the measured fluxes. We have checked from many theoretically known line ratios that these errors are realistic, the few discrepancies being indeed similar in both PNe. The models matched essentially all line fluxes within these errors, no more than a few percent for most basic lines. The two discrepancies left (the most significant one with argon) turned out to be virtually identical for both PNe, again suggesting systematic errors.

Despite the very strong and numerous observational constraints, it was possible to generate several satisfying models for each PN, as three useful line fluxes (C II 4267Å, [O II] 3726Å and [S II] 4069Å) were not accurate. Moreover, the uniqueness of the solution broke down to some extent in the case of He 2–436, the high density of the inner shell making the [O III] line ratio to depend on both temperature and density. Although the range of allowed abundances was still quite large for He 2–436, abundance ratios were much better defined.

In Table 1 the helium and oxygen abundances by number relative to Hydrogen and other abundances relative to oxygen are given. Clearly, Ne/O, S/O and Ar/O decrease from Wray 16–423 to He 2–436. Since S and Ar are unlikely to be synthesized in the parent star of Wray 16–423, this trend must be interpreted as an increase of oxygen abundance.

In Table 2 a possible evolution of the stellar envelope composition (abundances are by number in units of H $= 10^5$) is sketched, assuming that (1) S is constant with time within uncertainties and (2) O varies linearly with

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TABLE 1

ABUNDANCES

Ratio	Wray 16–423	He 2–436
He/H	0.1080±.0015	0.1080±.0025
$10^5\times$O/H	21.4±.2	24.±4.
C/O	3.3±.3	5.0±.8
N/O	0.213±.015	0.116±.006
Ne/O	0.168±.003	0.147±.005
S/O	0.0201±.0008	0.0167±.0013
Ar/O	0.0042±.0004	0.0029±.0007

TABLE 2

EVOLUTION

Stage: Elemt	Init	1st dg up	3rd dg up (Wray)	3rd dg up (He–2)
O	(16.5)	16.5±3.2	21.4±.2	26.0±2.0
C	$\sim$ 5.	4. – 3.	69.±5.	122.±18.
N	$\sim$ 1.	2. – 3.	4.6±.3	3.0±.2
Ne	-	-	3.59±.06	3.87±.13
S	-	-	0.44±.02	0.44±.02
Ar	-	-	0.09±.01	0.07±.01

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C during 3rd dredge-up (cols. 4, 5). Once the S abundance is specified for He 2–436, the range of accessible C and O abundances is narrowed. Then, based on the differential C enrichment and taking into account correlations between C and O in He 2–436 models, the increment ratio by number is ΔO/ΔC = 0.07 ± 0.04. The inferred main-sequence abundance of oxygen (cols. 2, 3) is significantly less than the PN values. The initial C and N abundances (col. 2) are "reasonable" guesses such that, after 1st dredge-up (col. 3), N is getting about its abundance in He 2–436 (col. 5; see below). The particular choice of the initial C is of no consequence for the derived initial O.

Ne and Ar appear approximately constant. The possible slight increase of Ne with C is far less than the "decrease" of N, thus probably excluding an extensive conversion of N into heavier elements along with 3-α burning. On the other hand, it is not clear why the 1st dredge-up would be more efficient in Wray 16–423 than in He 2–436 and it is unlikely that the 2nd dredge-up could operate in a low-mass star. Also He is equally enhanced in both PNe. May some kind of "cold bottom processing" (Boothroyd & Sackmann 1999) has converted recently synthesized ^{13}C into ^{14}N before dredge-up? Can this processing be more effective in conditions where the final C overabundance is less extreme? These questions are up to stellar evolution theory.

More accurate and more complete observations (UV, near IR) of Wray 16–423 and He 2–436 are needed to improve these preliminary results. New constraints, for example from different recombination lines, may lead to a revision of some model assumptions and/or challenge the view that these PNe are of common origin.

Meanwhile, stellar and galactic evolution theories may have to consider the implications of a possible synthesis of oxygen by low-mass stars. Spectroscopy of [WC] stars and recent star models of late thermal pulses (Herwig et al. 1999) agree that O/C may be even larger than our ΔO/ΔC. The question of how much of this oxygen is effectively expelled and mixed in the interstellar medium is to be investigated.

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