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OXYGEN AND NEON ABUNDANCES IN PLANETARY NEBULAE

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RESUMEN. Se han determinado las abundancias de oxígeno y neón para 171 nebulosas planetarias en la Galaxia, las nubes de Magallanes, y en M31 usando datos espectrofotométricos de la literatura y procedimientos de análisis estándar. Las abundancias logarítmicas de estos dos elementos varían universalmente al mismo paso, en forma idéntica a la que se observa en regiones H II. El cociente interestelar de Ne-O está controlado probablemente por estrellas masivas que representan un intervalo estrecho de masa. Los límites superiores en la producción de Ne y O por estrellas de masa intermedia fueron calculados de la dispersión en la relación Ne-O y se encontraron que están muy por abajo de los valores predichos para estrellas masivas.

ABSTRACT. Oxygen and neon abundances for 171 planetary nebulae in the Galaxy, LMC, SMC, and M31 have been determined, using spectrophotometric data from the literature and standard analysis procedures. The logarithmic abundances of these two elements vary universally in lockstep in a manner essentially identical to that observed for H II regions. The interstellar Ne/O ratio is probably controlled by massive stars representing a narrow range in mass. Upper limits on Ne and O production by intermediate mass stars were calculated from the dispersion about the Ne-O relation and found to be well below predicted values for massive stars.

Key words: **ABUNDANCES — NEBULAE–PLANETARY**

I. INTRODUCTION

Planetary nebulae represent the endpoint of evolution for intermediate mass stars (IMS) whose masses range from 0.8 to 8$M_\odot$. In terms of abundances, the nebulae consist of both material which has been synthesized and ejected by the star during its evolution, as well as unaltered interstellar material which the star inherited when it formed. Thus, studies of abundance patterns in planetary nebulae help shed light on both IMS nucleosynthesis and local interstellar abundances.

I have begun a project whose purpose is to study the abundances of a large sample of PNs which are distributed over several host galaxies. One of the principal aims of this work is to produce an homogeneous set of abundances by combining several sets of spectrophotometric data available in the literature with a single set of algorithms and atomic data.

The first phase of this project involves the study of O and Ne in 171 PNs representing the Galactic disk and halo, the Magellanic Clouds, and M31. In the current paper I summarize the results of the O-Ne study which has been published in Henry (1989). In addition, I employ these results to establish upper limits on O and Ne production by IMS and compare these limits with published theoretical and empirical results for massive stars.

II. OXYGEN AND NEON ABUNDANCES IN PLANETARY NEBULAE

The sample of 171 planetary nebulae used to study the abundances of O and Ne in PNs was compiled from lists of objects analyzed by Aller and Czyzak (1983), Jacoby and Ford (1986), Aller and Keyes (1987), Monk, Barlow, and Clegg (1988), and Boroson and Liebert (1989). Included in the list were the five Galactic halo PNs listed in Peña et al. (1989). Abundances by number of O and Ne were computed for each of these objects using spectrophotometric data published either in these papers or in others cited therein. The technique employed for obtaining the element abundances was the standard one in which ion abundances are determined directly from line strength ratios and are subsequently adjusted for unobserved ions. The program and atomic data used are discussed in detail in Henry, Liebert, and Boroson (1989).

The fundamental results of the analysis are presented in Figure 1 which is a plot of logarithmic Ne abundance by number (where $\log H = 12$) versus that of O for the 171 objects. The solid line is a least squares fit to 160 of the PNs (five halo, five LMC, and one M31 object were excluded), calculated using the regression technique described by York (1966), which allows for scatter in both coordinates. The dashed lines are located at perpendicular distances of $\pm 1\sigma$ from the solid line. The dotted line is a least squares fit to the Ne and O abundances for H II regions published by Vigroux et al. (1987). For three of the halo objects, more than one set of spectrophotometric measurements were used to obtain abundances; thus, the symbol positions in these instances represent unweighted averages of the results, and the error bars show the range of O and Ne abundance values obtained for each object.

The slope of the log-log plot for the PNs is +1.13, while that for the H II regions is +0.98. The standard deviation in these values is ±0.04 and ±0.06, respectively. The PNs are dispersed about the solid line with $\sigma = \pm 0.10$.

The basic conclusion to be drawn from Fig. 1 is that within the errors, and except for 2 halo PNs, the abundances of Ne and O in both PNs and H II regions increase together linearly in a manner which is independent of host galaxy. Furthermore, this behavior reflects the fact that the levels of these two elements rise and fall together in the interstellar medium, and these changes are tracked by both object types .

The closely coupled behavior of Ne and O seen in both PNs and H II regions strongly suggests that the interstellar Ne/O ratio is constant everywhere. As determined from the PN data, this ratio by mass is 0.21±0.06, a number which compares favorably with Kaler's (1978) results for Galactic PNs and Vigroux et al.'s (1987) results for H II regions. For the Galaxy, LMC, and SMC, the average values for Ne/O by mass are 0.21, 0.20, and 0.19, respectively. The three objects in M31 also exhibit the same Ne-O correlation. Thus, the implication is strong that the Ne/O ratio is a universal one.

Since it is apparent that Ne and O abundances in PNs are not influenced by IMS nucleosynthesis (see below), the levels of these elements must be the inherited ones and thus reflect the state of affairs in the interstellar medium at the time the progenitor stars formed. In this case, the most likely explanation for the observed Ne-O pattern is that the product of massive star yield and the initial mass function integrated over stellar mass is constant in time and space. Since Ne and O are synthesized by processes having different temperature sensitivities, one would predict intuitively that their production ratio varies over the mass spectrum. (If this variation is sufficiently large, the constant interstellar Ne/O ratio also suggests the existence of an IMF which is spatially and temporally non-varying.) But more than likely, the effective mass range for Ne and O production is rather narrow, being bound above by the declining initial mass function and below by objects having too little mass to produce these two elements. According to Nomoto (private communication), the centroid of this mass range is probably close to $20M_\odot$, although this number is sensitive to the uncertain $^{12}C(\alpha,\gamma)^{16}O$ rate as well as details of semi- convection, overshooting, and Coulomb interactions in the stellar core.

III. ESTIMATING UPPER LIMITS TO YIELDS OF O AND Ne IN IMS

One would not expect IMS to contribute significantly to the synthesis of O or Ne. This conclusion is suggested by synthesis predictions from a number of theoretical studies (c.f. Renzini and Voli 1981), and by the above empirical result that the abundances of Ne and O appear to vary together in the interstellar medium. In the latter case, significant production of one or both of these elements by IMS whose masses span a range from 0.8-8$M_\odot$ would most likely not produce PNs having nearly the same Ne/O ratios or a Ne-O relation for the population which resembles so closely the one for H II regions. However, we can use the dispersion of O and Ne about the linear regression for PNs in Fig. 1 to establish upper limits on Ne and O production by IMS.

To do this, I first equate the stellar production (yield) of element X (where X is either O or Ne) for a PN progenitor with the difference between the PN mass fraction for X, $Z_{PN}(X)$, and the analogous value for the nearby interstellar medium, $Z_{H\ II}(X)$, this difference multiplied by the mass of the PN, m_{neb}, i.e. $[Z_{PN}(X) - Z_{H\ II}(X)] \cdot m_{neb}$. (Notice that although IMS production of Ne and O should actually be measured by comparing PN levels with abundances of these elements at the time of progenitor formation, H II region values are employed here instead, even though they are no doubt higher due to element buildup over time.)

The critical simplifying assumption made here is that all newly synthesized material is lost only during PN formation and not during any preceding wind episodes. Future theoretical studies will determine whether or

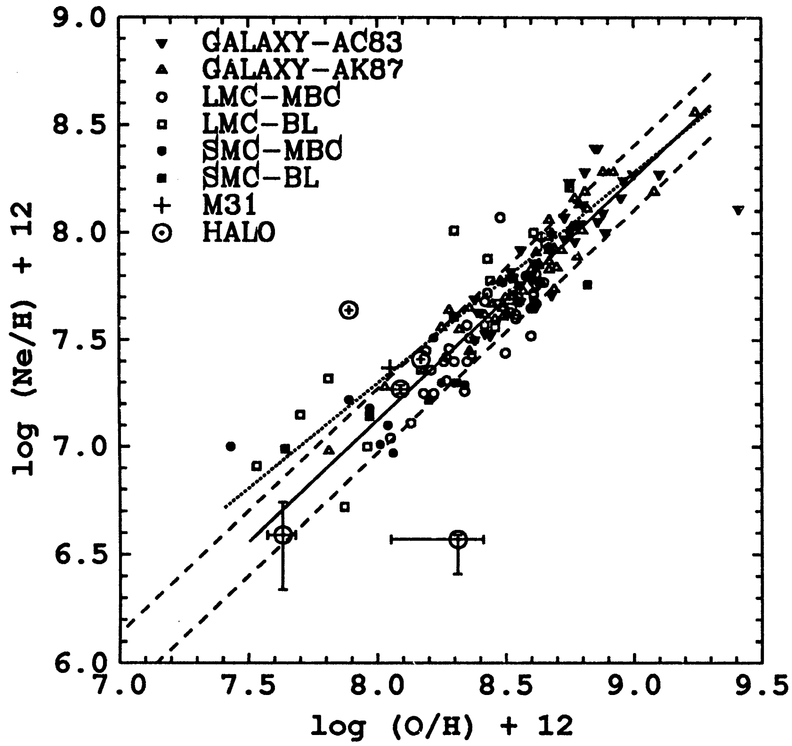

Fig. 1. Logarithmic number abundance of Ne/H versus O/H for 171 planetary nebulae located in the Galaxy, LMC, SMC, and M31. Abbreviations for data sources are: AC83: Aller and Czyzak (1983); AK87: Aller and Keyes (1987); MBC: Monk, Barlow, and Clegg (1988); BL: Boroson and Liebert (1989). The M31 data are taken from Jacoby and Ford (1986) while the data for Galactic halo objects came from Peña *et al.* (1989) or ones cited therein.

not this approximation is justified. Now,

$$Z_{PN}(X) - Z_{H\ II}(X) = Z_{H\ II}(X)\left[\frac{Z_{PN}(X)}{Z_{H\ II}(X)} - 1\right]. \tag{1}$$

Expressing the first term on the left in terms of quantities observed in H II regions within the same galaxy,

$$Z_{H\ II}(X) = \frac{A_X}{1+4\frac{He}{H}} 10^{\log(\frac{X}{H})_{H\ II}}, \tag{2}$$

where A_X is the atomic weight of element X, and He/H and X/H are the interstellar (H II region) abundance ratios by number. Finally, the ratio of mass fractions is equal to $10^{d\log\frac{X}{H}}$, where the exponent is a number to be determined from Fig. 1. Eq. (1) now becomes:

$$Z_{PN}(X) - Z_{H\ II}(X) = \left(\frac{A_X}{1+4\frac{He}{H}}\right) 10^{\log(\frac{X}{H})_{H\ II}} \left[10^{d\log\frac{X}{H}} - 1\right]. \tag{3}$$

The quantity $Z_{PN}(X) - Z_{H\ II}(X)$ was computed for the LMC and SMC PNs using the H II region abundance data from Dufour, Shields, and Talbot (1982). The value for $d\log X/H$ was set equal to the 3σ

dispersion in O or Ne of 0.21 determined from the fit for PNs in Fig. 1 above. The idea here is that any O or Ne synthesis could not raise the levels of these elements more than 3σ above the baseline value (as determined in H II regions) without causing the Ne-O relation for PNs to be different from that for H II regions. The resulting changes in mass fractions, as determined from eq. (3), were then multiplied by the average nebular mass of $0.27 M_{\odot}$ taken from Barlow (1987), who found the range in this number to be rather small.

The results for the upper limits for O and Ne stellar production for IMS in the LMC and SMC are presented in Table 1, where the numbers are expressed in solar masses. For comparison purposes, I have also listed the predicted O and Ne nucleosynthesis products for the progenitor of SN 1987A from Woosley, Pinto, and Weaver (1989) and Hashimoto, Nomoto, and Shigeyama (1989). These numbers are typical of the theoretical massive star yields summarized by Woosley and Weaver (1986) for stars of 12-100$M_{\odot}$. Ideally, the IMS limits for Ne and O production should be compared with abundance results for young oxygen-rich supernova remnants, whose progenitors were probably massive stars. Unfortunately, it is difficult to determine masses for observed nucleosynthesis products from studies such as those by Kirshner *et al.* (1989) and Blair *et al.* (1989), principally because the remnant mass itself is generally very hard to infer accurately. However, when Blair *et al.*'s estimate of the remnant mass of SNR 1E 0102.2-7219 is combined with the abundances of Ne and O which they determine for this object, the resulting yields are reasonably consistent with the model predictions for massive stars. In any case, the exercise presented above would seem to further substantiate the claim that IMS contribute little to the gradual buildup of Ne and O in the interstellar medium of their host galaxy.

IV. SUMMARY

Abundances of O and Ne have been computed for a sample of 171 planetary nebulae representing 4 different host galaxies. The levels of these two elements were found to be coupled in a manner nearly identical to what is observed in H II regions. The Ne/O ratio for the entire sample (excluding the 5 halo objects) was found to be 0.21 ± 0.06 by mass, in good agreement with previous studies of both PNs and H II regions. A linear regression was calculated for Ne versus O and the dispersion about the line was employed to place upper limits on O and Ne production. These upper limits were found to be far below the levels predicted for massive stars, thereby reinforcing the current assumption that IMS do not contribute significantly to the interstellar levels of O and Ne.

TABLE 1. O and Ne Production in Stars

	O[1]	Ne[1]
IMS (observed)[2]		
LMC	$< 5.0\times10^{-4}$	$< 1.3\times10^{-4}$
SMC	$< 2.4\times10^{-4}$	$< 5.7\times10^{-5}$
Massive Stars (Theory)		
WPW89[3]		
$18M_{\odot}$	0.24	0.15
$20M_{\odot}$	1.60	0.19
HNS90[4]		
$20M_{\odot}$	1.49	0.26

[1]Quantities are expressed in units of $M_{\odot}$
[2]Upper limits computed in this paper
[3]Woosley, Pinto, and Weaver (1989)
[4]Hashimoto, Nomoto, and Shigeyama (1989)

Studies such as the one detailed here show that planetary nebulae, through their ability to track interstellar levels of elements heavier than nitrogen, offer an opportunity to establish age-metallicity relations for the nearby galaxies in which they can be observed. Galaxies such as the LMC and SMC, which apparently possess no abundance gradients, seem especially attractive for such a study. The Ne/O ratio determined from PN studies would seem to be more accurate than the solar value determined from cosmic rays (Cameron 1982). Thus, numbers presented here offer the theorist in stellar evolution a "target" value for guiding model-building and ultimately, perhaps, for further constraining the $^{12}C(\alpha,\gamma)^{16}O$ rate.

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