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EXTREME CARBON ENRICHMENT IN A PLANETARY NEBULA

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ABSTRACT

The planetary nebula Hf2-2 (PK 5-8°1) is highly enriched in both helium and carbon but has a near-normal, roughly solar nitrogen-to-oxygen ratio. The C/O ratio appears to be the highest yet known.

Key words: planetary nebula–element abundances–temperatures–stellar evolution

I. Introduction

The study of planetary nebulae allows us to examine the stars that illuminate and produce them. The most familiar example is the computation of the stellar effective (Zanstra) temperature from the Hβ and He II λ4686 fluxes. Less familiar, but also of great significance, is the use—at least the potential use—of the chemical composition of the gaseous shell to deduce the initial nature of the progenitor star. It is now well known that planetaries can be enriched in helium, nitrogen, and carbon as a result of thermonuclear processes and mixing that took place on the giant branch prior to nebular ejection: for reviews see, for example, Peimbert and Torres-Peimbert (1983), Kaler (1983*a*, 1985*a*), Aller (1984), Pottasch (1984), and Clegg (1988). The degree of enrichment is expected to be a simple function of initial stellar mass (Becker and Iben 1979, 1980; Renzini and Voli 1981), and, consequently, the observed abundance ratios should provide us with that datum. This analysis, coupled with the calculation of the Zanstra temperature and luminosity of the final core, allows us in principle to use the nebula to help trace the evolution of the star from birth to death.

The details of the picture are not quite so clear, however. The observed correlation between N/O and He/H is roughly as expected through the second dredge-up stage and can at least be made to fit reasonably well for the third (Kaler 1983*a*, 1985*a*). However, the scatter of the data around the mean curve is very large, and the compositions of many objects fall well away from what is predicted. The situation is worse for carbon, where the helium-enriched nebulae do not follow the C/O–He/H prediction at all well. Although we can probably identify massive progenitors by large nitrogen and helium enhancements (Peimbert (1978) Type I objects), we cannot yet be quantitatively exact. Theory (as well as observation and interpretation) must be improved so as to explain the scatter of points and the extremes in the relevant correlations.

The extreme objects, those that should lead the way in the development of new theory, are relatively rare: only a handful of Peimbert Type I are known, for example. It is therefore of considerable interest and significance when a new one—this time carbon rich, as described below—is found.

II. The Observations

A. *Lines*

In the course of a large spectrophotometric study of planetary nebulae now underway (Kaler 1985*b;* Kaler, Shaw, and Kwitter 1988) a few objects with odd characteristics stand out, usually because of powerful nitrogen or ionized helium lines or because the emissions are more appropriate to a symbiotic star than to a planetary. The nebula under discussion, however, Hf2-2 (5-8°1 in Perek and Kohoutek's 1967 catalog, also known as He2-407), was immediately noted for its powerful line of C II λ4267, one of the strongest ever seen, clearly indicating a high carbon content.

The initial observations were taken with the 84-in (2.1-m) telescope and the IIDS at Kitt Peak (used in a remote mode with the observer at Illinois). The spectrum, acquired on 1983 September 10 through the 8.4-arc-second aperture in a 20-minute blue (λ3400–λ5200) exposure in the usual beam-switching arrangement, was reduced with Kitt Peak software with the comparison stars Kopff 27 and BD +28°4211 (Stone 1977). The scan immediately showed the unusual nature of the object, but because it was obtained at high air mass ($M \approx 4!$) it was considered to be unsatisfactory for use because of the large correction required for atmospheric extinction and, more importantly, because of uncertainties introduced by atmospheric dispersion.

Consequently, an additional exposure, presented as

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Figure 1, was obtained 1987 August 28 with the University of Arizona Steward Observatory 2.3-m telescope and the blue Reticon detector. Again, the object was beam-switched, with another 20-minute exposure, this time with dual 5-arc-second apertures. However, the wavelength range was larger (λ3700 to λ6800) and the air mass far lower, $M \approx 2.7$, which, although still fairly high, allows for reasonably reliable spectrophotometry.

Both spectra were analyzed with the Gaussian-fitting routine SPEC (see Kaler 1985*b*) from which the integrated line fluxes were determined. The relative line fluxes, on the usual scale $I(\mathrm{H}\beta) = 100$, are shown for each in Table I. They are not averaged because of the high air mass of the IIDS observation. The Steward data are intrinsically more reliable and are adopted for further analysis. The KPNO intensities provide a confirmation. Approximate errors can be assessed by comparing the two data sets. Given the high atmospheric-absorption corrections, the two sets of data are in remarkably good agreement, which will give credence to other observations in this survey that were necessarily obtained at high air mass.

While the Steward data are generally superior, they do suffer from an additional problem. The spectrum was acquired with a 400 line mm^{-1} grating used in the first order. The Reticon is extremely blue-sensitive, and the second-order blocking filter leaks enough ultraviolet light that the standardization longward of 6000 Å is unreliable, and therefore the Hα flux cannot be accurately related to Hβ. The red data were adjusted during reduction by an extrapolation of the instrument sensitivity function. Still,

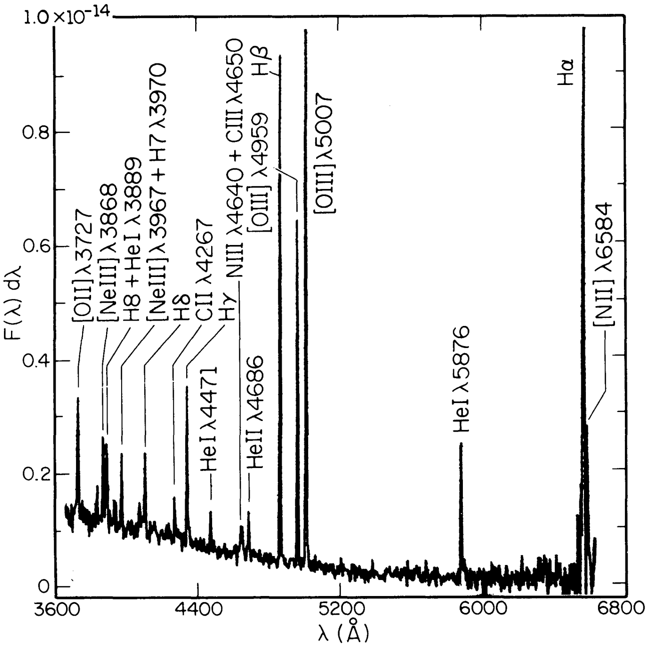

FIG. 1–The Steward Observatory spectrogram of Hf2-2, expanded vertically to show the weaker lines. Hα and [O III] λ5007 are cut off at the top.

TABLE I
Observational Data for Hf2-2
Relative Line Strengths

λ	ID	KPNO IIDS	Steward Reticon
3727	[O II]	23	32
3797	H 10	4	...
3819	He I	1	...
3835	H 9	5	5
3868	[Ne III]	21	23
3889	H8, He I	14	20
3967+70	[Ne III], H 7	18	18
4068+76	[S II]	9	8
4101	Hδ	22	20*
4267	C II	10	9
4340	Hγ	44	35
4363	[O III]	<2	...
4471	He I	7	7
4640	N III	12	5
4650	C III	...	5
4686	He II	9	9
4861	Hβ	100	100
4959	[O III]	75	75
5007	[O III]	252	244
5876	He I	...	36†
6548	[N II]	...	23†
6563	Hα	...	558†
6584	[N II]	...	43†
6678	He I	...	16†
	Hβ Flux		
10^{14}S(Hβ) ergs cm^{-2} sec^{-1} arcsec^{-2}		0.22	0.29
log F(Hβ)		-12.24	
	Stellar Magnitude		
B		18.0	17.5
V		...	18.2

* The peak intensity, normalized to Hγ, is 18: see § III.

† Uncertainly calibrated relative to Hβ: see § IIa.

they appear to be reasonably accurate. The nebula Abell 14 was observed on the same night, and comparison of the [N II]/Hβ flux ratio (Hα was too weak) observed here and with the IIDS earlier (unpublished) suggests an increase of 8% in the Hα and [N II] fluxes of Hf2-2. The Hα flux expected on the basis of recombination theory (Brocklehurst 1971) and the extinction as determined from the relative Hγ and Hδ intensities (§ III) gives a correction of unity; the difference could easily be due to errors in the extinction and to stratification in [N II]. Nevertheless, further analysis of the red lines will use only their more accurate flux ratios relative to Hα.

Absolute Hβ surface brightness in units of 10^{-14} ergs cm^{-2} sec^{-1} arc sec^{-2} can be calculated from the integrated Hβ fluxes and the spectrograph apertures. These are given in Table I below the relative intensities. The agreement is remarkably good. Here it is best to use a mean since, although the Steward data were acquired at a better air mass, the KPNO observations used a larger aperture, better averaging spatial fluctuations.

B. *Stellar Magnitude*

The spectra of Figure 1 both show a prominent continuum rising into the blue, as befits a hot nucleus, which can be seen easily on the blue POSS print. Continuum flux measurements at λ5480 (0.25×10^{-15} ergs cm^{-2} sec^{-1} $Å^{-1}$) and at λ4370 (0.78×10^{-15} and 0.57×10^{-15} for Steward and KPNO, respectively) then will yield V and B magnitudes. We must first correct these fluxes for the nebular continuum, which is relatively weak. From Pottasch (1984), the Hβ fluxes as determined through each aperture, the known reddening (see § III), and an electron temperature of 10,000 K, the correction at V is 34% and at B is 5% for Steward and 20% for Kitt Peak (the larger KPNO correction is expected due to the larger aperture).

When compared to the absolute flux for $V = 0$ from Oke and Schild (1970) and for $B = 0$ as determined from that work and the energy distribution of Vega from Hayes (1970) and Hayes and Latham (1975), we find the B and V magnitudes given at the end of Table I. A lower electron temperature of 7000 K (see § III) produces essentially the same result. The B values should be averaged to yield $B = 17.8$. The $(B-V)$ color index is meaningless because of the errors caused by the weakness of the continuum, particularly at V. These figures are supported by Kohoutek's (Perek and Kohoutek 1967) determination of $M_{ptg} = 17.4$ (corrected to 18.1 from Shaw and Kaler 1985) as determined from the image size on the blue POSS print. Although the values in Table I are probably good only to a few tenths of a magnitude, they are adequate for the calculation of Zanstra temperatures.

III. Analysis

Before undertaking a quantitative examination of the spectrum, let us look at two oddities: First, the aforementioned strength of C II λ4267, which is nearly 10% that of Hβ, and with a correction for reddening (see below) nearly 12%, making it about the strongest known. The line is clearly from the nebula proper and not from the star, since the strength relative to Hβ is the same in both spectra and is not sensitive to a factor of three change in aperture area. Second, note the anomalous weakness of [O III]. These lines reach maximum strength as He^{+2} begins to develop (Kaler 1978), and at this He II line strength they should overwhelm Hβ, yet they are only comparable to it, indicating either very low O/H, electron temperature, or both.

The data of Table I were analyzed with two extensive codes, one that calculates Zanstra temperatures and luminosities (Kaler 1983*b*) and another that produces densities, temperatures, and chemical compositions (Kaler 1985*b*) with the atomic data given by Brocklehurst (1971, 1972) and Mendoza (1983). In each case we first need an evaluation of interstellar extinction. The object has not been observed in the radio, and the Hα/Hβ flux ratio and $(B-V)$ for the star are both unreliable, so that we are left only with the relative intensities of Hγ and Hδ (Table I). These, unfortunately, have a short wavelength base relative to Hβ, which exacerbates intensity errors. Moreover, Hδ is blended at this dispersion with N III λ4097, λ4103, which can increase the relative flux by some 10% or so. In order to obtain the best estimate, we should use only the Steward observations, and instead of using the ratio of the Hδ and Hβ areas (integrated fluxes), use the ratio of peaks, which are less subject to blends. The peak intensities of Hγ and Hδ are 31 and 16, respectively, which represent reductions from the area ratios of 0.89 and 0.80. If we then normalize the Hγ peak and area ratios, we should increase the Hδ peak intensity by 1/0.89, or 1.12, resulting in $I(\mathrm{H}\delta) = 18$. Then from Whitford's (1958) extinction function (see Kaler 1985*b*) and Brocklehurst's (1971) theoretical intensities, the reddening constant (logarithmic extinction at Hβ) is $c = 0.99$ for Hγ and 0.82 for Hδ, resulting in a mean of 0.88 ± 0.06, exactly the value derived from the uncorrected but corroborating intensity of Hα. This constant is placed on the left side of Table II where we begin to accumulate stellar and nebular characteristics.

The distance and radius can next be calculated with the Shklovsky method under the conditions set forth by Cahn and Kaler (1971) from the angular radius, the total Hβ flux, and the above extinction. The radius, taken from Perek and Kohoutek (1967) is 8.5 arc seconds. If we assume that the nebular surface is uniformly illuminated, we can derive the flux from the Hβ surface brightness of Table I, whence $F(\mathrm{H}\beta) = 5.75 \times 10^{-13}$ ergs cm^{-2} sec^{-1}, or $\log F(\mathrm{H}\beta) = -12.24$. Because the nebula is only about twice the size of the IIDS aperture, and since $S(\mathrm{H}\beta)$ is fairly independent of aperture size (attesting to reasonable uniformity), this figure should be fairly accurate, probably to within a few hundredths. The resulting distance and radius, given in Table II, may or may not be correct since the input parameters (specifically nebular mass) are uncertain, but at least the method allows a comparison with other planetaries. The object appears to be rather large, 0.16 pc in radius, and thus would be considered optically thin.

This judgment is supported by the Zanstra temperatures, also given on the left in Table II, as calculated from $F(\mathrm{H}\beta)$, $I(\lambda4686)$, c, and the magnitudes of Table I. The fairly large errors primarily reflect the inconsistency between B and V. Nevertheless, it is apparent that T_z (He II) $> T_z$ (H), which is consistent with a nebula that is optically thin in the hydrogen Lyman continuum but thick in that of He^+. However, note that He II Zanstra temperatures for planetaries in general are consistently above those derived from line-profile fitting by Méndez *et al.* (1987) (see Kaler 1988). An effective temperature of ≈ 60,000–65,000 K, the mean of T_z (H) and T_z (He II), might be more fitting.

The luminosities are based on the temperatures presented in Table II and the Shklovsky distance. The errors

TABLE II

Analysis of Hf2-2

Nebular and Stellar Characteristics		Composition	Te = 10,000 K	7000 K
Extinction, c	0.88±0.06	He^+/H^+	0.173±0.003	0.156±0.005
Angular Radius	8.″5	He^{+2}/H^+	0.008	0.008
log F(Hβ)	-12.24	O^+/H^+	2.4×10^{-5}	1.4×10^{-4}
Distance	3900 pc	O^{+2}/H^+	8.4×10^{-5}	1.4×10^{-4}
Radius	0.16 pc	N^+/H^+	4.9×10^{-6}	1.4×10^{-5}
T_z(H)	50,000±10,000 K	Ne^{+2}/H^+	4.0×10^{-5}	2.2×10^{-4}
T_z(He II)	77,000±6,000 K	S^+/H^+	5×10^{-6}	2×10^{-6}
L_z(H)	240±50 $L_\odot$			
L_z (He II)	790±250 $L_\odot$	He/H	0.181	0.163
$\langle N_e \rangle$	450 cm^{-3}	O/H	1.1×10^{-4}	5.0×10^{-4}
T_e	≤10,200 K	N/O	0.21	0.10
		Ne/O	≥0.36	≥0.44
		C/H	2.1×10^{-3}	2.2×10^{-3}
		C/O	19	4.4

again reflect those in *B* and *V* as well as that in extinction. The values are considerably more uncertain than quoted because of the unspecified (and unknown) error in distance.

Since no p^3 doublet ratios (e.g., the λ6731/λ6717 flux ratio of [S II]) were observed, from which the density can be directly derived, it is necessary to calculate a simple rms density based on radius, Hβ flux, and an adopted filling factor of 0.65. As a result of the large size the density is low, a bit below 500 cm^{-3}.

The [O III] electron temperature of 10,200 K is calculated from a *very* uncertain intensity of the auroral λ4363 line (which for better accuracy is scaled to Hγ, thence to Hβ through the theoretical Hγ intensity), whose detection may actually be no more than a noise bump. The temperature therefore represents more of an upper limit. However, it is exactly the value expected for a nebula with this level of helium ionization (Kaler 1986*a*). The [N II] auroral line at λ5754 is too weak to be seen, but since we would similarly expect T_e [N II] to be 10,300 K, a round value of 10,000 K is at first adopted for the following abundance calculations.

The nebular composition, derived from the dereddened intensities of Table I and the above parameters, is presented on the right in Table II. The He^+/H^+ ratio was derived from an average of those calculated from λ4471 and λ5876, to which was applied the collisional corrections formulated by Clegg (1987). From the low error we see that they give almost the same high result. The λ6678 line, though clearly present, is too weak relative to the noise to be used, but it gives a confirming value of $He^+/H^+ = 0.21$. The O^+ and O^{+2} abundances are low, as expected from the weakness of the lines. The N^+/H^+ ratio was calculated from the [N II]/Hα flux ratio, so the uncertain calibration of the red part of the spectrum plays no role.

The total abundances are given below the ionic. He/H is just the sum of the two ionic ratios, and O/H is the sum of O^+/H^+ and O^{+2}/H^+, multiplied by the small correction factor $(1 + He^{+2}/He^+)$ to account for O^{+3} (Seaton 1968). N/O is as usual set equal to N^+/O^+.

The carbon abundance, the focus of this paper, presents a problem as the optical lines have traditionally given higher values than the ultraviolet, possibly due to uncertainty in the λ4267 effective recombination coefficient (see Kaler (1986*b*) and references therein). It would in principle be better to use the UV lines, but this object is too faint and too highly reddened to be easily accessible with *IUE*. The C/H ratio in Table II is calculated with the algorithm given by Kaler (1983*a*), which contains a correction from C^{+2} to total C through an ionization curve, and scaling to what would be expected from ultraviolet observations by means of a set of nebulae observed in both spectral regions.

The results of the calculations show heavy enrichment in both helium and carbon, with the former double the solar value and C/O up from solar (which, from Ross and Aller (1976), is 0.45) by a factor of about 40! However, the O/H is suspiciously low, only ≈ 10^{-4} (compare with Kaler's (1980) compilation), so that the high C/O of 19 may be an artifact. The observed [O III] λ4363 line may well not be real, and the electron temperature may be too high. The abundances were therefore recalculated for a variety of temperatures. At 7000 K, the results for which are also presented in Table II, the O/H ratio has climbed to a more reasonable 5×10^{-4}, which drops C/O to a less astonishing (but still very high) value of 4.4 (and decreases He/H a bit to 0.163). It is unlikely that O/H would be any higher, thus providing a lower limit to C/O. In both cases, however, the N/O ratio stays low, between 0.10 and 0.21, which encompasses the solar value of 0.15 (Ross and Aller 1976).

We might also think to fault Kaler's (1985*a*) algorithm. As an alternative, we can calculate the expected C III] λ1909 intensity from I(λ4267) and Kaler's (1986*b*) empirical relation, and then derive C^{+2}/H from the formula given by Aller (1984). If we do we find an even higher ratio of C/O; so for further discussion, let us stick to the values of Table II.

IV. Discussion

Compare these abundances with Kaler's (1983*a*, 1985*a*) graphical compilations, which are reproduced in Figure 2. The upper limit to He/H is nearly twice normal, and the allowed range places the object within the top five to ten known. Even the lower limit to C/O makes Hf2-2 the third or so most carbon-rich planetary (and the upper limit sets the record). Yet the low N/O makes the nebula quite anomalous, as high He/H almost always goes hand in hand with high N/O. If we place the nebula on each of these two figures we see that the object is simultaneously at the upper-right extreme of the C/O plot and at the lower-right extreme of the N/O graph.

Qualitatively, the object fits the picture presented for the third dredge-up by Becker and Iben (1980), which in its simplest form shows that C/O and He/H should both increase along with initial stellar mass, whereas the N/O should first rise, then level, and even fall a bit. At its upper limits Hf2-2 has C/O and He/H both above the theoretical limits expected at highest mass, and N/O considerably lower than anticipated. However, at the lower limits the C/O and He/H fit the Becker and Iben (1980) theoretical curve almost perfectly for a star with an initial mass 7 times solar. Under any circumstances, however, N/O is well below the N/O, He/H curve.

Finally, Aller (1983) and Torres-Peimbert (1984) suggest an anticorrelation between N/O and O/H. Might we be seeing the same effect here, with depletion of oxygen accompanying the enrichment of carbon as indicated by the higher temperature results? Such a suggestion is supported at either temperature by the large neon-to-oxygen ratio. Kaler (1980) demonstrated that Ne/O is nearly constant among planetaries at 0.225 ± 0.01. Moreover, in the excitation range appropriate to Hf2-2, neon is nearly all in the Ne^{+2} ionization state, so that Ne^{+2}/O is not far below the true Ne/O. From Table II we see that Ne/O is $\gtrsim 0.36$, 60% or more larger than typical. Ne/O decreases with an increase in T_e or with a decrease in c, but we cannot drive the ratio down to "normal" with any realistic combination. If O/H is actually depleted, then 7000 K is too low (as O/H is then appropriate to a nebula in the galactic disk), and the points that represent this nebula in Figure 2 are both up and to the right of the minimum along the connecting bar. A temperature of

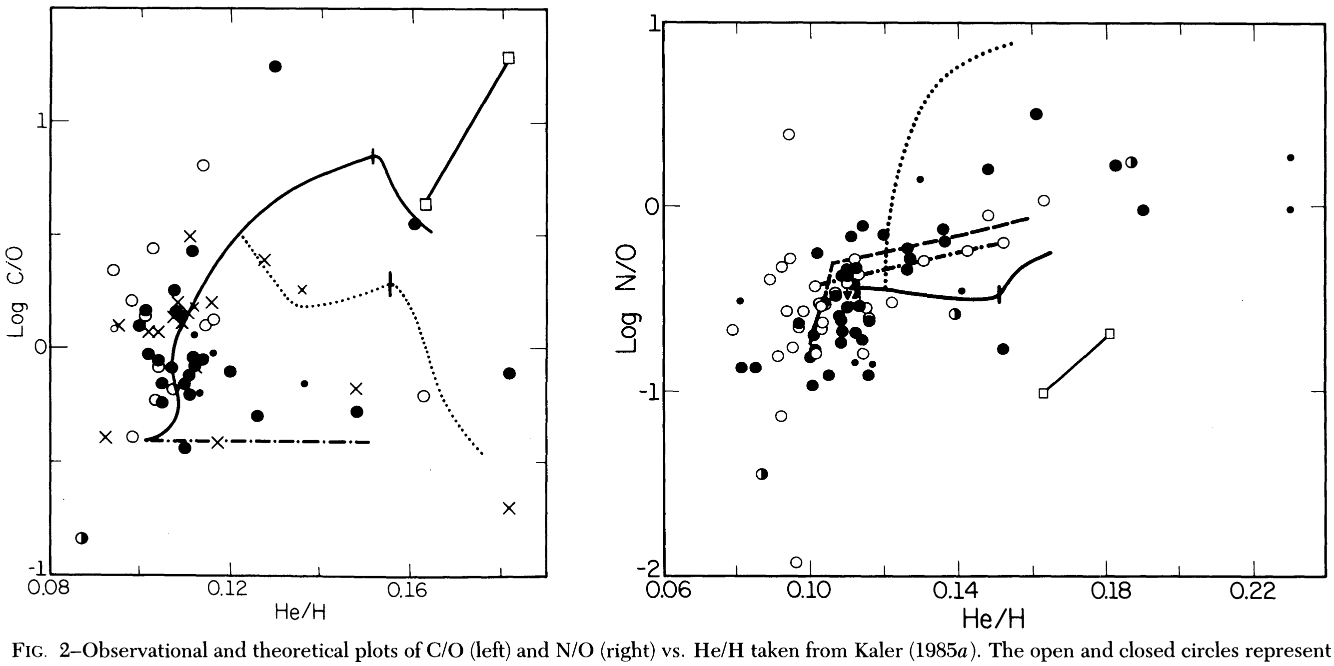

FIG. 2–Observational and theoretical plots of C/O (left) and N/O (right) vs. He/H taken from Kaler (1985*a*). The open and closed circles represent Populations I and II, respectively; the Xs represent UV data. Solid line: predictions for third dredge-up (d.u.); dotted line: third d.u. with hot bottom burning; dashed line: third d.u. with conversion of C to N in envelope at one-half the maximum rate; dot-dash line: second d.u. only. Maximum and minimum values for Hf2-2 are shown by the connected boxes.

8000 K is perhaps a better minimum, one that gives consistency with some oxygen depletion relative to a typical normal galactic value. This temperature yields O/H = 2.7×10^{-4}, C/O = 8.0, N/O = 0.13, and He/H = 0.170.

Whatever the details of the above arguments, the object is highly enriched in carbon and helium, implying a high initial mass, and thus raising an additional problem. A star with an initial mass as high as this one is expected to be should also have a high core mass: over 1 $\mathfrak{M}_\odot$ from Iben and Truran (1978) and of the order of 0.7 or 0.8 $\mathfrak{M}_\odot$ from Kaler's (1983*b*) analysis of N/O ratios. Yet the Zanstra temperatures and luminosities of Table II place the star below a core mass of 0.55 $\mathfrak{M}_\odot$ (the star falls inside the curve traced by Schönberner's (1981) evolutionary track: see Kaler 1983*b*). Either: (1) the star has lost much more mass than expected; (2) lower-mass stars can produce very high C/O and He/H; (3) the distance, and hence the luminosity, is wrong; or (4) and most likely, some combination of the first three.

Under any circumstances, however, this planetary nebula with its unusual composition, and a handful of others like it (both observed and to be found), will inevitably lead the way to an improvement in theory.

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