ABUNDANCES IN PLANETARY NEBULAE

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1. Introduction

Good progress has been made since the last Symposium on the determination of planetary nebulae (PN) abundances. Notable features for modern abundance determinations include the availability of good collision strengths and transition probabilities (reviewed by C. Mendoza (1983) at the last meeting - IAU Symp.103), the use of the IUE & IRAS satellites to obtain UV & IR line fluxes, and the availability of modern sensitive detectors enabling measurements both of faint extra galactic nebulae and of very weak abundance-indicator lines in nearby bright nebulae. The impact of IUE on PN studies was described by Köppen & Aller (1987).

PN abundance results tell us about mixing processes in the envelopes of red giant stars. HII regions provide much better indicators of galactic abundance gradients; the PN are a relatively old population. Discussions on PN abundances were given by Kaler (1983a), in the books by Pottasch (1984) and Aller (1984), and in the review by Kaler (1985). A related review, on nucleosynthesis and mixing processes in PN progenitor stars was given by Iben & Renzini (1983).

For low and intermediate mass stars, Iben & Renzini describe three 'dredge-up' events. In the first, material processed in the CN cycle during main-sequence evolution is mixed out to the surface. The N abundance rises while the C and the $^{12}C/^{13}C$ ratio both drop. The second dredge-up is predicted to occur only for higher masses, $\gtrsim 2.5 - 8M_\odot$, and the products of intensive CNO-cycle burning are mixed out. Surface He and N abundances increase, while those of C and O fall (O by less than C). The third event occurs on the Asymptotic Giant Branch (AGB): products of He-burning are dredged-up to the surface during stellar thermal relaxation oscillations. The products - mostly ^{12}C and heavy elements made in the s-process - are subject to limited CN-cycle burning on the way out, so that some conversion from C to N and production of ^{13}C are both facilitated. In general, the O abundance is predicted to be the least affected of the CNO group, and it is a prediction of the current theory that planetary oxygen abundances should be very close to the initial stellar abundances. The dredge-up episodes are subject to modification when rapid rotation produces significant internal circulation currents (Sweigert & Mengel 1979).

S. Torres-Peimbert (ed.), Planetary Nebulae, 139–156.

Peimbert (1978) classified PN in four groups: Type I are He-and N-rich, and are bi-polar with filamentary structures. Peimbert & Torres-Peimbert (1983) listed 29 such objects with defining abundance characteristics He/H > 0.125 or N/O > 0.5. They are Population I objects close to the Galactic plane and have evidently suffered the 2nd dredge-up. From the binary nuclei of NGC 2346 & 3132, and from NGC 2818 which is probably connected with the open clusters of the same name, Peimbert & Serrano (1980) estimated for these Type I nebulae that a lower limit on the initial mass which produces the He - N rich PN is about 2.4 $M_{\odot}$. Peimbert (1985) has reviewed additional evidence that the Type I progenitor stars have masses $\gtrsim$ 3 $M_{\odot}$. This fits in with current ideas about the 2nd dredge-up, although the lower mass limit for this is very dependent on modelling parameters such as convective mixing length.

Type II and III are disk planetaries with low and high dispersions, respectively. Type IV refers to objects in the Galactic Halo, of which only 4 definite members are known (see Sec.5). Faundez-Albans & Maciel (1987) have suggested that it would be useful to divide the Type II group into subtypes (a) and (b) according to whether the nitrogen abundance log(N/H) + 12 is more or less than 8.0. Subtype (b) objects have a smaller velocity dispersion than (a), and the suggested subdivision could be useful in studies of Galactic abundance gradients and the relative ages of different PN samples.

2. Helium Abundances

He/H ratios in planetary nebulae tell us about the dredge-up of helium (eg in Type I objects), the pregalactic helium abundance (from Type IV objects) and give a calibration for $\Delta Y/\Delta Z$, the relative increase by mass of He and heavy elements during galactic evolution (eg Maciel, these proceedings). The standard method of abundance analysis is to use the effective recombination coefficients of Brocklehurst (1971, 72) for H and He together with observed fluxes of He recombination lines such as $\lambda\lambda$4471,4686,5876 and 6678Å. But the interpretation of HeI lines is complicated by the meta-stability of the lowest triplet levels 2s ^{3}S. Collisional excitations from this level can excite all the observed HeI "recombination" lines. This subject has a long history and a large literature (see Peimbert & Torres-Peimbert 1987 and Clegg 1987a; respectively PTP87 and C87).

Analysis of HeI collision strengths of Berrington et al. (1985) by Ferland (1986) resulted in Ferland's correction formulae to allow for collision excitations of HeI lines. But improved calculations (Berrington & Kingston 1987) recently yielded much lower collision strengths, and updated correction formulae are available from PTP87 and C87. The two sets of correction formulae are not the same. PTP87 derived empirically the ratio, γ, of the 2 ^{3}S population to that predicted theoretically (from the balance between recombinations (arrivals) and collisional transfers to singlet levels (departures). From new line fluxes for Type I nebulae and published λ10830 Å fluxes, they found $\gamma = 0.5 \pm 0.2$. It was suggested that additional physical processes were de-populating the 2 ^{3}S level in nebulae. In contrast C87 included collisional ionisation of He(2 ^{3}S), took only 50% of the theoretical collision rates to the n = 4 levels, assumed $\gamma = 1$ and tried to see if the resulting corrections were "plausible". It was shown that the hypothesis, that He abundances should not depend on nebular temperature and density, is better satisfied for 3 of 4 data samples when corrections are applied. C87 found that the mean He/H ratio for non-Type I PN is 9% lower after corrections, with He/H = 0.099 ± 0.007 (He/H = 0.105 if Type I objects are not excluded from typical data samples).

What is the cause of these discrepant findings? Clegg & Harrington (these proceedings & in preparation) found that photo-ionisation of He 2 ^{3}S (I.P = 4.77 eV) can alter the metastable's population by anything from zero to 20%. A recommended prescription will be given by them. This, together with collisional ionisation, goes some way towards an agreed final value for γ. Fortunately, total He/H ratios are not much different whichever current prescription for collisional effects are used. For example, from new line data (PTP87) for 13 Type I PN, the mean He/H ratio is 0.131 with C87's prescription and 0.135 with PTP87's, a difference of only 3%. My current recommendation is to work with all three lines λλ4471,5876 & 6678Å, use either C87 or PTP87 together with the recombination coefficients of Brocklehurst (1972), and check for the presence of neutral helium using the criteria either of Kaler (1978) or Torres-Peimbert & Peimbert (1977) for low-excitation nebulae. If He^o is present, a lower limit for He/H is obtained. (For Type I or very high excitation PN, photoionisation models show that a larger fraction of H^o than He^o exists - this also affects He/H ratios, but this time in the opposite sense - observed ratios need to be decreased).

Although the drop in PN helium abundances is only ~ 9%, these results indicate that the self-enrichment in He of non-Type I PN is small, since the mean value now equals that of HII regions (eg Dufour 1984). The same result is found for Large & Small Magellanic Cloud PN & HII regions (Monk et al. 1988): data for HII regions and non-Type I PN are all consistent with He/H = 0.085 ± 0.004 for both Clouds. This raises the question: are Type I objects really a separate class? Although there is a continuous sequence of observed He/H and N/O ratios in planetaries (eg Kaler 1983a), on theoretical grounds Type I nebulae can be viewed as a separate group if they all arise from progenitor stars having $M \gtrsim 2.5_\odot$, where the 2nd dredge-up has operated. Peimbert & Torres-Peimbert (1983) discuss additional ways in which these objects form a coherent group.

Three interesting consequences of these collisional effects are noted. Firstly, abundances of other elements may change because several ionisation correction factors (icf's) depend on the derived ratio of He^+/He^{++}, which is now altered. Secondly, the Galactic enrichment of He by planetaries is lowered somewhat. Peimbert (1987) showed that most of the He production is by Type I nebulae (which give 3-6 times the contribution of Types II & III), and the helium enhancements in these objects is now lower by ~ 25%. Thirdly, a revised estimate for the pre-galactic He/H ratio can be obtained. I have re-calculated this using the method of Peimbert (1983) based on abundances in the four known PN in the Galactic Halo (see also Sec.5). It is assumed that the current He/H ratios in these objects reflects the pre-galactic value plus enhancements only from the progenitor's 1st and 3rd dredge-ups.

The results are shown in Table 1. y denotes the He/H ratio by number and Y the mass-fraction of He; 'new' refers to results including allowance for collisional effects, and ΔY values are calculated enhancements in the 1st and 3rd dredge-ups, so that $Y = Y_p + \Delta Y^1 + \Delta Y^3$.

Table 1 Pre-galactic Helium Abundance Y_p

Nebula	y^{old}	y^{new}	Y	ΔY^1	ΔY^3	Y_p
K648	0.096	0.083	0.263	0.014	0.014	0.235
H4-1	0.103	0.095	0.282	0.014	0.054	0.214
BB-1	0.101	0.090	0.276	0.014	0.036	0.226
DDDM-1	0.106	0.086	0.276	0.019	-	0.257

The mean value is $Y_p = 0.23 \pm 0.03$ (or He/H = 0.076 ± 0.010). There are two uncertainties in the method used: the prescriptions for the ΔY values are from Renzini & Voli (1981) and are really only valid for stars of higher initial mass, and secondly for DDDM-1 which has a very low carbon abundance I assumed no 3rd dredge-up has occurred. In fact in the initial shell flashes of AGB evolution He-rich material might be picked up without the convective region reaching down to carbon-polluted layers (Schonberner 1979); but on the other hand for these low-mass Pop II stars the very first shell flash may mix out sufficient carbon to cause the surface C/O ratio to exceed unity and even drive envelope ejection (A. Renzini, these proceedings). No correction has been made for neutral helium in the nebulae, for all of which the relation $O^+/O^{total} \leq 0.4$ holds (a value above 0.4 suggests the significant presence of He^0, Torres-Peimbert & Peimbert 1977).

Although this value of Y_p is less precise than that obtainable from extragalactic HII regions, this method does give an independent check on this important quantity. Maciel (these proceedings) has used Type II PN together with extragalactic HII regions to find a value Y_p in the range 0.23 to 0.24, in agreement with and more accurate than the value from halo PN alone.

3. Mean Abundance in PN Samples

3.1. Nebulae in the Galactic Disk

In the last ten years abundances for large samples of nebulae have been given by Torres-Peimbert & Peimbert (1977), Barker (1978), Aller & Czyzak (1983;AC) and Aller & Keyes (1987;AK). I restrict discussion to studies since the 1982 PN Symposium. AC & AK use a combination of empirical analysis of observed optical and UV ionic lines, plus results from photo-ionisation models to correct for un-observed ionic stages. AC analysed 41 nebulae, and AK give data for 51 additional PN; together with published material, abundances of some elements in up to 104 PN are listed.

Abundances can be presented relative to H or relative to O. It is well-known that on average PN have O/H roughly half the Solar value (eg $\langle O/H \rangle = 4.3 \times 10^{-4}$ (AK) while the Solar photospheric value is 8.3×10^{-4}, Lambert 1978). Three possible reasons why O/H is low include: (i) the PN constitute an old disk population similar to the Mira variables, and this is on average metal-poor (ii) there are temperature fluctuations within the nebulae - allowance for these could raise the oxygen abundance to the solar value (eg Dinerstein et al. 1985), although such fluctuations are not understood and are arbitrary at the moment (iii) the reduction in the O abundance is larger than predicted by stellar evolution theory. In this context abundance results for 30 cool carbon stars by Lambert et al. (1986) are relevant: they found a mean O/H ratio of 4.6 (±1.4) × 10^{-4}, a value very similar to that for planetaries. From Na,Ca & Fe lines it was found that the (uncertain) mean "metal" abundance (M/H) lay between 0.5 - 1.0 × Solar. Thus we do not have strong evidence yet on the relative variation of oxygen and "metals" from the main sequence to PN phase.

I assume for now that these O-deficiencies are not due to mixing processes or temperature fluctuations, and present in Table 2 below mean elemental abundances, relative to oxygen, in the AC and AK samples and in a merged mean. In the last column the dredge-up process which may be responsible for a non-solar abundance ratio X/O is identified. Note that both these samples contain Type I nebulae. Incidentally, AK provide a large number of references to individual nebular abundance determinations published since 1982.

The C/O and N/O are unquestionably enhanced in PN; this is surely due to mixing processes in the progenitor stars. Similar results obtain in Magellanic Cloud nebulae: for example, Monk et al. (1988 and these proceedings) derive a very similar nitrogen enhancement for 71 Cloud PN to that listed here, and Aller et al. (1987) describe C and N enhancements in 12 nebulae in the Large & Small Clouds.

Table 2 Mean Abundances in Disk Planetaries*

Element	AC	AK	log(X/O)	[X/O]	Dredge-up
C†	8.78	8.74	0.09	+ 0.29	3
N	8.26	8.39	- 0.26	+ 0.65	1,2,3
O	8.64	8.65	0.00	-	None
F	4.6:		- 4.0:	0.3 ± 0.4?	None
Ne	8.03	8.01	- 0.64	+ 0.18	3?
Na	6.18		- 2.46	+ 0.13 ± 0.15?	None
S	7.00	7.04	- 1.61	+ 0.03 ± 0.1?	"
Cℓ	5.22	5.32	- 3.33	0 ± 0.1?	"
Ar	6.43	6.46	- 2.19	0.11 ± 0.15	"
K	4.95		- 3.69	0.04 ± 0.15	"
Ca	5.03		- 3.61	- 1.1 ± 0.2	(grains)

* In the form log(N/H) + 12. [x] denotes $\log(x/x_{\odot})$.
† From UV lines only. Mean is higher if λ4267 is included.

Unfortunately there is an uncertainty in the carbon abundances, due to the fact that C^{++}/H^{+} ratios derived from the CII λ4267Å recombination line are often (but not always) much higher than those found from the collisionally-excited CIII 1908Å line. The cause of this is unknown, and C abundances listed here are from UV lines.

Zuckerman & Aller (1986) analysed the CNO abundances in the AC sample together with some results from the literature. They found that of 68 PN, 62% had $C/O > 1$. The same fraction was obtained for a subset which were clearly bipolar in shape (thus bipolarity is not a characteristic of C-rich evolved stars only). The ratio (C+N+O)/H lay between 0.34 and 1.7 times the solar value for 42 of 44 objects (here, the effects of the 1st & 2nd dredge-ups are removed, since the sum of C+N+O does not change in the CN + ON-cycle burning). It then seems unlikely, incidentally, that any significant fraction of PN progenitors are hydrogen-deficient; Goebel & Johnson (1984) suggested that cool carbon (N-type) stars might be H-deficient as an explanation for the weakness or absence of H_2 vibration-rotation lines therein, but Lambert et al. (1986) found this discrepancy vanished when model atmospheres including polyatomic molecules were used. To my knowledge there are no H-deficient planetary nebulae, except for the central cores of A30, A58 and A78 (see Sec.6).

In the above discussion it was assumed that the oxygen abundances are unaltered by mixing processes. In fact small reductions can occur in the 1st & 2nd dredge-ups. But even for massive progenitors, $M \sim 7\ M_{\odot}$, the models (Renzini & Voli 1981, Renzini 1984) give a maximum reduction in the surface O abundance of 30% even after the thermal pulsing phase (3rd dredge-up). I draw attention to results for Type I nebulae (Peimbert & Torres-Peimbert 1983, 1987) and luminous Population I stars (Dufour, these proceedings), a few of which show large oxygen deficiencies and an anicorrelation between N and O abundances, such that O+N is approximately constant. The most likely explanation is processing of a substantial fraction of the envelope mass through the ON-cycle. In this case the O and He abundances should also be anti-correlated: when the temperature is high enough for the ON-cycle to operate, a significant fraction of H will be converted to He. Note that these objects with reduced O are sufficiently rare (thanks to their high masses and the steepness of the initial mass function) that they do not make a significant effect on the mean O abundance given in Table 2. An example of a Type I nebula with low oxygen is Hu 1-2, which has $O/H = 1.6 \times 10^{-4}$ and $N/O = 1.4$ (PTP87).

While there is clear evidence of alteration of carbon & nitrogen abundances in PN, the situation for neon is more marginal. Ne is predicted to be produced from fresh ^{14}N in the intershell region during AGB thermal pulsing, at least for the more massive progenitor stars, via the reactions $^{14}N(\alpha,\gamma)\ ^{18}F(\beta^{+},\nu)\ ^{18}O(\alpha,\gamma)\ ^{22}Ne$. If the surface enhancement is large enough, then the Ne & C abundances should be correlated in PN. (Note that the fresh neon has mass 22, while the original surface material would be more than 90% ^{20}Ne. Unfortunately there is no known way yet of measuring neon isotope ratios in nebulae). Table 2 shows that while the mean Ne/H ratio in bright disk PN roughly equals the "Solar-System" value, the mean Ne/O of 0.24(± 0.01) for 102 nebulae (AK) is nominally higher than the recommended "Solar" value of 0.16(± 0.05) (Anders & Ebihara 1982). The latter authors show that the ratio obtained from measurements of the Ne/Ar ratio in the Solar wind ($Ne/O = 0.21$) is much higher than the value obtained from hot stars & HII regions ($Ne/O = 0.13$, Meyer 1979). Since there is evidence that elements in the Solar wind are fractionated by ionisation potential, it is better to compare PN abundances with those in hot stars and HII regions.

The mean value of Ne/O in disk PN is certainly higher than the value 0.13 from Meyer's careful review, and this suggests that PN may indeed have enhanced neon abundances. Correlations with carbon abundances should be looked for. The production of ^{22}Ne is likely to be more efficient in higher-mass stars, and indeed in a new analysis of 12 Type I nebulae (PTP87), it was found that the mean Ne/O ratio was 0.28 ± 0.05, a value even higher than that of 102 disk nebulae. Note that more work is needed on icf's for neon, for cases where UV and infrared data are unavailable (then, the NeIV and NeII may not be observed). In particular, the icf scheme $Ne/H = (Ne^{++}/O^{++})(O/H)$ will not be accurate when there is a significant fraction of H^{o} present, because charge-exchange reactions affect Ne and O quite differently. Since the Solar-System Ne/O ratio is not well-known, a careful comparison of PN and HII region ratios is now needed.

3.2. Galactic Bulge Nebulae

Planetaries here are of interest because they constitute a sample at a known distance - that of the Galactic Centre - and are in a region with a different chemical history from the Solar neighbourhood. For example, the ratio of carbon stars to M giants is much lower in the Bulge. Price (1981) found one out of four nebulae there to have a high oxygen abundance, so is there a metal-rich PN population in the Bulge?

The answer seems to be "generally, no". Webster (1988) derived He, N & O abundances for 49 Bulge nebulae, and found most had oxygen abundances similar to those of disk PN. One candidate metal-poor nebula was found, and ten possible O-rich objects were identified for further study. 10-20% of the sample are Type I objects, giving evidence for a young component. Mean abundances for all 49 objects were $O/H = 5.4 \times 10^{-4}$, $N/H = 8.1 \times 10^{-4}$. Remarkable here is the high N/O ratio - more than twice the value for disk PN - which may be due to high N abundances in the progenitor stars: Lester et al. (1987) found from measurement of the IR fine-structure lines of NIII and OIII in HII regions that the N/O ratio was about a factor three higher near the Galactic centre than near the Sun (but see Rubin et al. 1988 for a critical discussion of this question).

Pottasch & Dennefeld (1985) presented some first results from a survey of Bulge nebulae, with most nebulae again having O/H ratios typical of disk PN. Webster (1988) gives discussions and references to this question generally. C/O ratios for some of this sample would be of interest, since there are so few carbon stars in this part of the Galaxy. Kinman et al. (1988) presented lists of newly-discovered PN in the Bulge, so the size of analysable samples is increased.

3.3. Abundance Gradients in the Disk

Kaler (1983a,1985) reviewed the evidence for apparent radial abundance gradients for PN across the Galactic disk. He concluded that the apparent horizontal gradients are partly if not wholly due to vertical (ie perpendicular to the plane) gradients. There are two other problems with the interpretation of apparent gradients: PN are self-enriched in some elements (especially, He in Type I nebulae and C and N in all types of nebulae), and secondly PN belong to an old disk population with a high-velocity dispersion - so they can have non-circular orbits round the Galaxy. HII regions are better monitors of actual abundance gradients.

New results on apparent gradients were given by Faundez-Albans & Maciel (1986,1987) who find measurable gradients in Type II PN for many elements. Earlier Maciel & Faundez-Albans (1985) observed an apparent gradient in electron temperature, which is most convincing for Type II nebulae and which was interpreted as due to a general abundance gradient (cooling by heavy elements is reduced for lower abundance nebulae at large Galactocentric distances). It is in this connection that the proposed subdivision of nebulae into Types IIa and IIb may be most useful, since class IIb has the smaller velocity and should represent a 'thinner' disk population than a general sample of disk planetaries.

3.4. Correlation with position in the HR Diagram

Both Kaler (1983b) and Gathier & Pottasch (1985) found important correlations between nebular abundance and the location of the central star on the (log L,log T) theoretical HR diagram. Kaler studied 57 large nebulae, and used HI & HeII Zanstra temperatures and luminosities. In his Fig. 11 he shows that nebular N/O ratios correlate with stellar properties in the sense that higher N/O is associated with higher core mass which result from stars of higher initial mass. Gathier & Pottasch studied a sample of nebulae thought to have reasonably well-known distances, and found that He and N abundances were on average higher for stars located near higher core mass tracks.

These results give another nice confirmation that N and He are being mixed out in PN progenitor star envelopes (especially in the 2nd dredge-up). Peimbert (1985) has reviewed further evidence that the He-and N-rich Type I nebulae must originate from stars of higher initial mass ($M_i \gtrsim 2.5\ M_\odot$).

4. Depletion of Elements in Grains

The elements Aℓ,Mg,Si,Ca & Fe have abundances in nebulae which can be much lower than Solar, and this is very likely due to depletion in grains, since these refractory elements are depleted also in interstellar clouds. Shields (1983) reviewed these depletions at the last symposium.

Harrington & Marionni (1981) measured Si and Mg abundances in 6 nebulae. Si/O ratios were 0.005-0.006 in 3 nebulae (cf the Solar value of 0.05) from the Si III] λ1883 line, a depletion of an order of magnitude. For magnesium they found that, for IC2165 & NGC2440, no single abundance could match the [Mg V] λ2783 and Mg II λ2800 line fluxes simultaneously, with the predicted Mg II flux much too strong. The same result for NGC 7027 led Péquignot & Stasinska (1980) earlier to suggest that some PN had a 'Mg-gradient': in the inner, highly-ionised regions Mg was mostly gaseous, but in the outer regions (Mg^+ zone) it had largely condensed in grains. Péquignot & Stasinska alsed used [Mg IV] and [Mg V] lines in NGC 7027 to support this argument.

Mendoza & Zeippen (1987) computed new collision strengths for Mg IV & Mg V (see Sec.8), which reduce but do not remove the need for a gradient in NGC7027. In a very detailed study of NGC3918, Clegg et al. (1987a; CHBW) showed that the Mg II λ2800 line was obliterated by interstellar absorption by Mg^+ ions. This line cannot be used for abundance work unless it can be shown that the interstellar lines are shifted completely clear of the nebular emission (eg, thanks to very high PN radial velocity). Middlemass (1988; and these proceedings) gives an atlas of high-resolution Mg II line profiles; the attenuation of the nebular line flux correlates strongly with the LSR radial velocity. Models were used to derive Mg/H ratios of 4,1 and 0.3×10^{-5} for IC418, IC4997 and NGC2440 respectively. CHBW derived Mg/H = 1.4×10^{-5} from [Mg V] and Mg I (λ4570) lines in NGC3918; the Mg I] can be used in models for abundances now that a charge-transfer rate for the reaction Mg + H^+ is available (Allen et al. 1988). The Solar Mg/H is 4×10^{-5}.

I conclude that (a) Mg II λ2800 must usually be corrected for interstellar absorption (this applies to CII λ1335 as well) (b) Mg depletion in grains is less than previously thought - typically a factor 3 and up to a factor 10 (c) the need for a 'gradient' in NGC7027 and NGC2440 is reduced but still not removed. It is not impossible that, with more accurate atomic data for al Mg ions and more refined PN models, the need for a gradient might vanish; the question is still open.

Depletions of iron can apparently vary greatly: Shields (1978) found for 6 nebulae a range of depletions from a factor 3 to 100. CHBW found that He was deficient by a factor 100 in NGC3918, from [Fe VI] and [Fe VII] lines. Some of the earlier work should be re-examined to (a) allow for new collision strengths for some Fe ions (b) investigate what nebular properties the depletion correlates with.

Are much of C,N & O in grains? Probably not. Clegg (1985) concluded that not more than 30% of C or O is likely to be condensed. Recently, Harrington et al. (1988; and these proceedings) modelled the thermal IR emission from NGC3918 (which has C/O = 1.6) with a size distribution of carbon grains. The implied depletions of gas phase carbon were only 11% and 4% for graphite or amorphous carbon grains, respectively. But it is not firmly known that the grains here are carbon at all - the measured depletions of Mg,Si & Fe (factors of 3,4 & 100) are already quite sufficient to provide the required volume of dust. Pottasch et al. (1984) found a correlation between gas-to-dust ratio and nebular radius: compact PN such as BD + 30° 3639 had a ratio $\sim 10^2$:1 while for large nebulae the ratio is nearer 10^4:1 by mass. Knapp (1985) found, from models of the dust and CO emission from the envelopes of AGB stars losing mass, that the average ratio was 400:1 for C-rich and O-rich objects. All these ratios are probably uncertain by a factor $\sim$ 3. Ratios below about 500 are 'dangerous' in the sense that the depletion of C or O could approach 30%. We need more detailed model analyses of samples of C-rich and O-rich compact PN to see if ratios $\sim$ 100:1 really can occur.

Ca is strongly depleted in many nebulae (see AC and Table 2), but S suffers either zero or rather small depletion (less than a factor two according to AC and AK). Aℓ was found to be heavily depleted in NGC6543 and BD + 30° 3639 (Pwa et al. 1984, 1986). In an interesting new method these authors used nebular absorption lines seen in high-resolution IUE spectra, as well as emission lines, to derive abundances (the method only works if the nebular absorptions are well-shifted in velocity away from the interstellar lines). Although depletion factors are variable in PN, the pattern does resemble roughly that seen in the diffuse interstellar clouds.

5. Galactic Halo Nebulae

Four nebulae - K648,H4-1,BB-1 and DDDM-1 - are located at large distances out in the Galactic Halo. They are of special interest because (a) they have low abundances (except for carbon) and an element mixture different from Solar (b) they give information on the evolution of extreme Pop.II stars (c) they have low content of refractory elements so the dust-to-gas ratio is worthy of study (d) they can be used to estimate the pregalactic helium abundance (Sec.2). Their abundances were reviewed by Clegg et al. (1987b) and Clegg (1987b), so discussion here is highly abbreviated.

Table 3 Halo PN Abundances*

Object	C	N	O	Ne	S	Ar
K648	8.7	6.5	7.7	6.7	5.2	4.3
H4-1	9.3	8.5	8.3	6.7	5.2	5.3
BB-1	9.1	8.5	7.8	7.7	5.7	4.6
DDDM-1	<7.1	7.4	8.1	7.3	6.5	5.8
<Disk PN>	8.8	8.3	8.6	8.0	7.0	6.4

*log(N/H) + 12. References in Clegg et al. (1987b).

Abundances, in the form log(N/H) + 12.0 are given in Table 3. The objects fall in two groups. For K648,H4-1 & BB-1: S and Ar are much more deficient than N,O & Ne; C abundances are solar or greater so that C/O ratios are large. For DDDM-1: all elements measured have roughly 1/6 the Solar abundance, except for carbon (which is not detected at all) and Mg (which is depleted by a further factor of 3). The first group suggest that the early Galactic halo had a very different ratio of 'light' (A<11) to 'heavy' (A>15) elements from the present-day disk. K648 is in the Globular cluster M15 which has [Fe/H] = - 2.1 (Fe/H 120 x below Solar), while the mean (Ar + 5) deficiency for K648 is 150 x below Solar. It would appear that S & Ar have varied in step with Fe during Galactic evolution. To test this idea further I have plotted in Figure 1 (taken from Sneden 1985) all 4 Halo objects by assuming that [O/(AR+S)] represents "[O/Fe]" and [(Ar+S)/H] represents "[Fe/H]". References for data on disk & halo stars are given by Sneden.

We see that if (S & Ar) are taken as surrogates for Fe, the halo PN and old stars show the same trend with metallicity - oxygen behaves the same relative to (S & Ar) as it does to Fe. One (but not the only) interpretation of this O/"Fe" relation is that Fe is produced mainly in Type I supernovae (SNI) while O is produced in massive stars. The latter evolve so much faster than the former that O/H rises faster than Fe/H

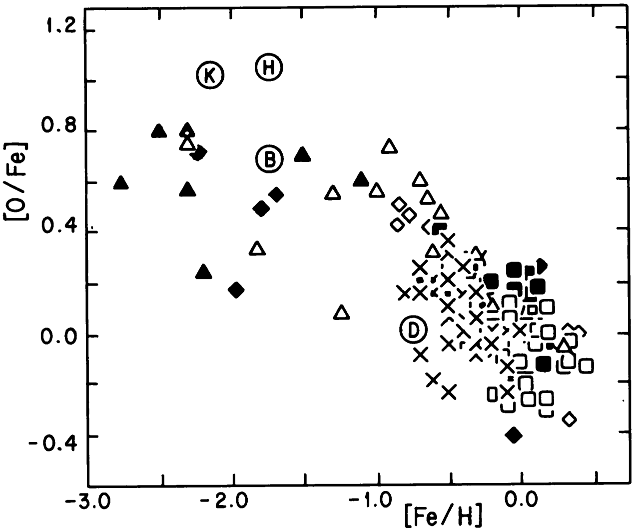

Fig.1 - Comparison of Halo PN & Halo Stars, when (S+Ar) is taken as surrogate for Fe. Halo PN symbols: H = H4-1, K = K648, B = BB-1 and D = DDDM-1. Figure from Sneden (1985).

during Galactic evolution (eg Matteucci 1987). For this scenario, we cannot have S & Ar made in massive stars or else O/(S+Ar) would be constant). The implication - that S & Ar are made in SNI-is of great interest for nucleosynthesis in supernovae: Nomoto (1985) has suggested that SNI contribute significantly to the production of elements in the Si-Ni range as well as Fe. Specifically, he has proposed a carbon-deflagration model and calculated yields of these elements. A competing, carbon-detonation model for SNI produces only Fe-peak elements. The halo PN results suggest that S & Ar are produced in a site similar to that of Fe production. Then for SNI the deflagration model is better. Analysis of old stars also shows that S,Ca and Ti vary in a manner intermediate between O and Fe (eg Francois 1987, Gustafsson 1987). Fuller discussion on nucleosynthesis in SNI & SNII is given by Nomoto (1985) and Thielemann & Arnett (1985) respectively.

The high-carbon abundances in three of the halo nebulae is presumed to be due to the 3rd dredge-up. However this presents a theoretical difficulty: that dredge-up should not have occurred at the low luminosities (a few × 10^3 $L_\odot$) corresponding to the tips of red giant branches in globular clusters (Renzini, these proceedings). Either the 3rd dredge-up is occurring at luminosities lower than predicted when the metallicity is ery low (c.f. the discovery of low-luminosity carbon stars in the Magellanic Clouds, which also disagreed with theory), or another process is at work. These three nebulae may be related to the giant CH stars (which may all be binaries). We need more accurate abundance analyses of the halo PN, more information on the central stars, and more discoveries of new halo PN to increase the sample size (currently DDDM-1 is in a class of one!).

6. CNO Abundances from Recombination Lines

Although these lines are weak in PN, they provide (a) abundance indicators for highly-obscured nebulae where no UV data are obtainable (b) possible diagnostics for electron temperature and (c) measurement of the attenuation of resonance lines by dust (eg from CIII λ2297, NIV λ1718. French (1983) obtained carbon abundances in 6 PN from optical recombination lines without recourse to UV data. Advantages of such lines are their insensitivity to electron temperature and their availability even in obscured objects. On the other hand they are weak, are sometimes blended, and require high-dispersion spectra. Moreover there is a serious outstanding problem for C^{++} abundances, where the CII λ4267 recombination line can give a factor 3-10 higher abundance than the CIII λ1908 collisionally-excited line (eg Kaler 1986; Barker 1987 and references therein).

In Table 4 I list some CNO lines that can be used. The OIV and NIV n = 6-5 lines were recently discovered in NGC3918 by Clegg et al. (1987a;CHBW); they are weak but provide useful diagnostics in bright, high-excitation nebulae.

Table 4 Some CNO Recombination Lines

Spectrum	λ(Å)	Transition	Type$^{(a)}$	Rate$^{(b)}$	Blends
CII	4267	3d ^2D - 4f $^2F^o$	R	1	-(?)
CIII	1577-78	3d ^3D - 3d $^3F^o$	D	2	[Ne V]
	2297	2p $^1P^o$ - 2p^2 ^1D	D	2	He II
	4070	4f $^3F^o$ - 5g ^3G	R	1	S II
	4187	4f $^1F^o$ - 5g ^1G	R	1	O II?
	4647-51	3s ^3S - 3p $^3P^o$	R,D	1,2	O II
CIV	4568	5g^2 G - 6h $^2H^o$	R	1	[Fe III]
	5801-12	3s ^2S - 3p $^2P^o$	R	3	-
NII	5666-88	3s $^3P^o$ - 3p ^3D	R	4	-
NIV	1718	2p $^1P^o$ - 2p^2 ^1D	D	2	-
	4606	5g ^3G - 6h $^3H^o$	D,R	2,3	-
OIV	1342	2p^2 ^2P - 2p^3 $^2D^o$	D	2	C II
	4632	5g ^2G - 6h $^2H^o$	R	3	-

(a) R = radiative, D = dielectronic recombination

(b) References for rates: 1 - Seaton 1977 2 - Nussbaumer & Storey 1984

3 - see CHBW page 561 4 - Wilkes et al. 1981.

The problem about C^{++} abundances mentioned above has also been with us for some years. CII λ4267 appears to be too strong in the integrated spectra of some nebulae, relative to CIII] λ1908; Barker (op.cit.) has shown that the discrepancy is often worst near the inner regions of extended nebulae. The problem can also be stated another way: as derived from the flux ratio λ4267/λ1908, $T_e(C^{++})$ appears to be very often lower than T_e measured from other ionic line ratios (eg Kaler 1986). Kaler suggested that a likely solution would be to increase the effective recombination coefficient for 4267 by a factor about four. However, this would not explain the spatial variation noted above. Here are 8 possible solutions to the problem, several discussed by Barker (1982) in Paper II of his series: (a) observational errors (b) charge-transfer reaction 'feeds' λ4267 (c) dielectronic recombination 'feeds' it (d) a blend with another line at 4267Å (e) λ4267 excited by fluorescence (f) nebulae temperature fluctuations (g) density fluctuations (h) C-rich knots occur in the inner regions of many PN.

Space permits only brief notes on these possibilities: (a) very unlikely now several independent groups note the problem. (b) the rate would have to be 10^4 times the theoretical rate (Butler et al. 1980). (c) found to be insignificant (Storey 1981). (d) should be checked with high-dispersion spectroscopy. (e) possible. Detailed quantitative models are needed, plus observations of other CII lines which would have to be excited too. For example, one possible mechanism - absorption of starlight exciting the CII 6d ^2D level - involves emission at 6622Å which is not seen, with upper limits for NGC7009 (U. Carsenty, private communication) and IC418 (Monk et al., in preparation 1988) ruling out this as a significant 'route' for excitation. (f) would work. But we see no other convincing evidence for the required level of fluctuations and they are not yet explained theoretically. (g) makes the problem worse (Mihalszki & Ferland 1983), (h) not predicted by stellar evolution theory to be common at all (though see Sec.7) but worth a critical observational & theoretical look. The cool knots would contribute only to the 4267Å emission in this scheme. The minimum mass of carbon required could be calculated - is it plausible?

It is worth noting that the line CII λ4267 gives a problem in absorption in B stars too (see Lennon 1983). LTE & NLTE analyses produce carbon abundances much lower than Solar - the line is weaker than expected. The B star and PN problems are in the same sense - the upper level of the transition (CII 4f $^2F^o$) is overpopulated relative to the lower level.

7. Abundance Variations within Nebulae

When PN show multiple shells, haloes or knots, are the abundances uniform across the whole nebula? To my knowledge the only convincing evidence for variations come from three objects - A30 and A78 (see Jacoby & Ford 1983, Iben et al. 1983, Manchado et al. 1988) and A58 (Seitter 1985, Pottasch et al. 1986) - which have H-rich outer regions and inner knots rich in He and heavy elements. Iben et al. interpreted such results for A30 & A78 in terms of a PN nuclei which had undergone a very late shell-flash, returned to the AGB and evolved off it again but now He-burning instead of H-burning. The products of helium-burning are ejected and seen in the inner knots (He,C). The central star of A58 had a 'nova-like' outburst in 1917, and in this case the central knot is only mildly He-rich. These objects are important, and Pottasch et al. note that A30 & A58 show extremely-large infrared excesses (A78 was not observed by IRAS), which might be used as a criterion for detection of further such objects.

PN with multiple-shells & haloes appear to have abundances constant within the errors. One element for which an internal gradient is of great interest is carbon, but the outstanding problem about C^{++} abundances (CII λ4267) make observational studies difficult. Jacoby et al. (1987) developed an imaging method to analyse NGC40 & NGC6826 at many positions, from calibrated CCD images taken in the light of Hβ, [OII], [OIII], [NII] & [SII]; no significant abundance variations were found. In a series of Papers, Barker (1987 and references therein) has analysed several positions in large nebulae, but again no convincing variations were seen. Space Telescope observations of the CII, CIII and CIV UV lines would aid a search for gradients and for C-rich inner knots.

8. New Collision Strength Calculations

I have included below a list of some new collision strengths published since Mendoza's (1983) compilation, and which may affect abundance determinations. There is no guarantee the list is complete; it comprises results that I or colleagues at University College know about. A reference to unpublished work implies that the data can be obtained from the authors listed. Note that the collisional strengths for the fine-structure lines of NeV (Aggarwal 1983) are not recommended here, for the reasons given by CHBW.

Some highlights are noted. The availability of good data for Ar IV is very useful. Derived Ar^{3+} abundances are affected, by up to a factor 2, and we can now use the [Ar IV] line ratio λ4711/λ4740Å more reliably as a diagnostic for electron density measurements. Secondly, an increasing number of infra-red fine structure lines can now be used for abundance work. Particular attention is drawn to observations of such lines as Ne VI at 7.6μm (Pottasch et al. 1986) and Si VI (1.96μm) & Si VII (2.48μm) by Ashley et al. (1987); these have been detected so far only in Type I nebulae. The new data permit derivation of Ne^{5+}, Si^{5+} and Si^{6+} abundances. The I.P. of Si^{5+} is 205.1 eV, so detection of Si VII attests to the very high temperatures of the central stars of Type I PN. Moreover,it suggests that such nebulae are so highly-ionized that ionisation correction factos (icf's) for heavy elements need to be evaluated very carefully in the study of these systems.

Two disadvantages of far-infra-red lines for abundance work in PN are that absolute flux calibration is difficult, and that the lines are density-sensitive (critical densities are often in the region of 10^3 - 10^4 cm^{-3}). The lines areparticularly important for the study of highly-obscured HII regions.

Table 5 New Collision Strength Data

Spectrum		
C II	10-state calculation.	Lennon et al. (1985), Hayes & Nussbaumer (1984)
N III	Fine-structure lines.	K. Butler & P.J. Storey (in prep.)
O IV		Hayes & Nussbaumer (1983)
Ne II	Fine-structure line.	Bayes et al. (1985)
Ne III	Fine-structure lines.	K. Butler (1984)
Ne IV	Fine-structure lines.	K. Butler & P.J. Storey (in prep.)
Mg IV	5-state calculation (incl. fine-str.).	Mendoza & Zeippen (1987)
Mg V	" " " " "	" " " "
Mg IV) Aℓ V)	Fine-structure lines.	K. Butler (in prep.)
Si III	Ultraviolet lines	Dufton et al. (1984)
Si VI) Si VII)	Fine-structure lines (near IR).	K. Butler (in prep.)
Ar VI	7-state calculation.	Zeippen et al. (1987)
Cℓ III	" "	K. Butler et al. (in prep.)
K V	" "	K. Butler et al. (1988)
Mg I	5-state calculation.	H.E. Saraph (In prep.)
Fe VII	Many transitions.	Keenan & Norrington (1987)

9. Concluding Remarks

New atomic data, new detectors and newly-opened spectral regions seen from space have improved our knowledge of abundances in planetary nebulae. The mixture of elements in most PN is non-Solar, with C and N the main culprits. There are some agreements with the nucleosynthesis & mixing processes described by current theory. An interesting figure is provided by Lambert et al. (1986) which shows the 'evolution' of mean C/H, N/H and O/H ratios from M/S stars via C stars to PN. The PN data arre from Aller & Czyzak (1983).

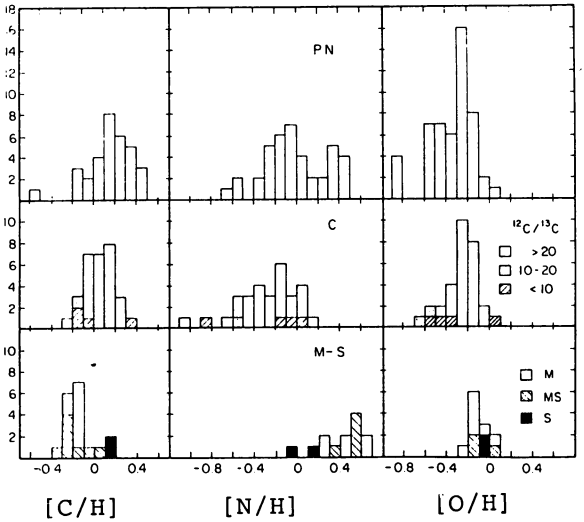

Fig.2 - Histograms of C/H, N/H and O/H for M & S stars (bottom), C stars (middle) and PN (top panel). Figure and references from Lambert et al. (1986)

Such plots are broadly encouraging. But there are plenty of problems. Examples include the large C abundances of 3/4 Galactic Halo nebulae, the low O abundances found in some Type I PN and shells around massive stars, a few high He/H ratios ($\gtrsim$0.18) in some Type I nebulae, the C^{++}(4267/1908Å problem, the depletion of carbon in dust. Future studies may usefully be directed at PN in specific locations (Galactic Bulge, Magellanic Clouds, other galaxies), accurate studies of Type I nebulae, search for new Halo PN and A30-type objects, and the systematics of dust in nebulae of different sizes, as this affects abundances.

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