Planetary Nebulae: An Introductory Review

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Planetary nebulae constitute a popular field of investigation because they offer a unique opportunity to study the final stages of stellar evolution before a star dies. They supply challenges not only to the stellar evolution expert but also to the spectroscopist, to the student of galactic structure, and to all observers, whether one works in the optical, ultraviolet (UV), infrared (IR) or radio-frequency (r.f.) ranges. They offer insights into properties of dusty, low-density plasmas which may help unravel problems of the interstellar medium (ISM) and quasars. Finally, many are aesthetically beautiful art creations.

Technological strides make possible great advances in studies of planetary nebulae (PN); the International Ultraviolet Explorer (IUE) has revolutionized PN researches in the UV, as will become abundantly clear in this conference. At the extreme other end of the spectrum, the Very Large Array (VLA) has been employed by Johnson, Balick, and Thompson (1979) to study compact PN, but it can also be used to obtain high-resolution images of more extended nebulae, and even investigate mass loss rates of planetary nebulae nuclei (PNN) (Thompson and Sinha 1980). The flying Kuiper Infrared Observatory has opened a new window on important IR atomic and molecular transitions in a dusty spectral domain. These techniques have improved our understanding of PN, but the most exciting advances may lie ahead. The astrometric satellite can supply trigonomeric parallaxes of bright planetary nebulae nuclei PNN. Alas, most PNN are too faint. High spatial resolution, now partly available for NGC 6853 and 7293, will be attained for many PN, and when we combine these data with correspondingly detailed kinematical information, we can substantially advance our understanding of structures of PN.

Certain basic statistics of PN are not well fixed. A reliable distance scale is fundamental. Among recent efforts are those of Acker (1978), Khromov (1979), Maciel and Pottasch (1980), and of Milne (1982). A popular idea is that we can start with an evolutionary scenario giving relations between the absolute magnitude M_s and temperature T_s of the central star, the radius R_n and surface brightness S_n of the nebula and lo presto we get a distance scale.

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These parameters must have an intrinsic spread and it may be a while before we get distances better than 10%. Our basic statistics on stellar PN may be fairly good to a faint limiting magnitude, but data on low surface brightness objects are badly affected by selection effects, especially interstellar extinction (ISE). Isaacman used the distribution of galactic center PN to get a galactic bulge mass model. His best fit gives 1.1×10^{10} m(sun) for the inner kpc and a mass luminosity (M/L) ratio ~ 5. He finds 300 PN within R = 0.3 kpc.

As for spatial distributions and motions of PN, although Paralta (1978) found low latitude PN moved in orbits with $\varepsilon \sim 0.2$, and Khromov (1979) concluded PN belong to an old flat Population I system, PN orbits are distinctly elliptical (Khromov; Purgathofer and Perinotto 1980). Other statistics important to PN as a group include the number per kpc^3, total number in our galaxy and other galaxies, masses of ejected shells, masses of progenitor stars (and spatial distribution of the same), the birth rate and luminosity function, see, e.g., Maciel's (1981) summary. Total masses of ejected shells are popularly taken ~ 0.2 to 0.4 m(sun); halo PN masses $\lesssim$ 0.1 m(sun), with the ionized mass only a small fraction of the total (Pottasch 1980). Jacoby (1980) finds luminosity functions in local group galaxies to be remarkably similar, fitting the idealized Henize-Westerlund (1963) model in which PN are regarded as uniformly expanding, homogeneous, gaseous spheres ionized by nonevolving PNN.

Approximate coincidences between PN birth rates and death rates of main sequence (MS) stars suggest that most in the range of 1 to 5 m(sun) eventually produce PN and return much of their mass to the ISM. Identification of immediate giant precursors of PN is difficult. Carbon stars, Mira variables, and "symbiotic" variables have all been invoked. At the risk of being vague, we can sketch reasonable scenarios. At the peak of its asymptotic giant branch (AGB) evolution, a star loses its outer envelope, maybe by pulsational instabilities or a "superwind." In the Kwok-Purton-FitzGerald KPF (1978) model, for example, the outflowing gas in a gentle wind that had been blowing during the AGB phase is suddently blasted by a stellar wind of ~ 1000 km/sec from the exposed hot core of the expiring star. Although this scenario has much to recommend it, many details need examination. Fragmentation of the ejected outer envelope and subsequent motions can be complex. Many investigations dating to the 1950's attest to the inhomogeneities in supergiant envelopes such as those of ζ Aurigae or 31 Cygni. It should not surprise us that PN start their lives as broken shells, rings, etc., with many condensations or blobs. Some of the proto-PN must be objects such as the bipolar nebulae GL 618 and M 2 - 9 (cf. Schmidt and Cohen 1981). Often, the character of the blobs can be inferred only indirectly from plasma diagnostics, but in some objects, e.g., NGC 6853 or NGC 7293, they can be studied directly and their relationship to the overall nebular structure established.

Dust seems to play an important role throughout the entire lifetime of a PN, although effects may be more dramatic in earlier stages. Dust masses seem similar from one PN to another, T(dust) ~ 100°K, and dust emission seems to favor H^+ regions (Moseley 1980). Despite its small contribution to a PN mass, dust can have important effects on gas phase fractions of refractory elements, on spectral line intensities, and on PN evolution. Iron (Shields 1978), magnesium (Pequinot and Stasinska 1980; Harrington and Marionni 1981), calcium (Aller 1978), and aluminum are examples of metals depleted by being locked in solid grains. In most PN, the solid particles are probably carbon; in Abell 30, Greenstein (1981) found that the extinction could be explained by soot! Cohen and Barlow (1980) separate PN from very low excitation (VLE) H II regions by the silicate emission in the latter. Aitken et al. (1979) find that some PN, e.g., Hb 12 and Swst 1 show silicate emission as do the Trapezium stars. Dust and gas can affect T_s determinations by Zanstra's method (Helfer et al. 1981).

Molecules can supply data on physical conditions in PN condensations, shielded zones, etc. We would expect large abundances of H_2, H_2^+, OH, and CH^+ in transition zones of ionized nebulae (Black 1978). In NGC 6720, Beckwith et al. (1978) find H_2 emission correlated with [O I], not H II zones. H_2 emission can be produced in clumps heated by an expanding H II region (Smith et al. 1981).

Turning to spectroscopy, note the great leap forward given by opening up of the UV, where fall precious transitions of He, C, N, O, Ne, and Si. Although most lines here are excited by collisions, processes such as dielectronic recombination become important for some. These UV lines offer many advantages for diagnostics and abundances. Much information is buried in many weak permitted transitions of abundant elements in the optical region. This spectroscopic source has been inadequately tapped since the pioneering work of Wyse (1942). Nikitin et al. (1981) used permitted lines of N III, C III, and C IV to get abundances of C and N in high-excitation PN, and to assess the role of spectral lines corresponding to two-electron excited states. Wilkes et al. (1981) used weak permitted ionic lines to get N abundance in NGC 3242.

Infrared fine structure transitions involving ions such as Ne II, S IV, and Ar III, which include some ionization stages not otherwise observed, offer important help for PN diagnostics and compositions (Grasdalen 1979; Aitken et al. 1979; Dinerstein 1980; Beck et al. 1981). We hope these data can be supplemented by observations from satellites.

Of fundamental importance to all spectroscopic studies and plasma diagnostics are accurate atomic parameters: A-values, Ω-values, recombination coefficients, and charge-exchange cross sections. Much progress has been made since Osterbrock's (1974) compilation. C.D. Keyes is preparing a summary of recent data. We are heavily indebted here, particularly to Seaton, Nussbaumer, Dalgarno, Czyzak, and their respective associates, and to the Belfast group.

Accurate chemical compositions of PN should assist in investigations of stellar evolution, nucleogenesis, and the history of the ISM. Some elements in all PN and perhaps all elements in some PN have not been transmuted in the nuclear furnace. What counts is not just the processing of H into He, and He subsequently into C, N, Ne, and N production by the CN cycle, but the mixing of these products into the outer layers which are eventually ejected as a PN. He, C, N, and possibly O, may be affected by nucleogenesis but elements heavier than

O certainly will not be, for m(*) < 5 m(sun). To what extent are observed abundance fluctuations real and how much do they reflect errors in analysis? Of course, the abundances of C and N which are important in the nucleogenesis scenario, are among the hardest to get, at least from optical data. N is represented only by [N I] and [N II], while most of its atoms are usually in higher ionization stages. Fortunately, the persevering efforts of Barker and Kaler have shown that $N/O = N^+/O^+$ to within a factor of 2 for many PN.

Given the observed line intensities and diagnostics, i.e., (T_ε, N_ε), we can get reasonably good estimates of $N(X_i)$, the number of ions of element X in the i^{th} ionization stage. The big problem is always to get N(X), the elemental abundance, expressed in terms of N(H), the hydrogen abundance. Three possibilities seem promising: a) simple ratios such as $(O^+ + O^{++})/H^+ = O/H$, $O/O^{++} \sim Ne/Ne^{++}$ work well in PN of moderate excitation but not for ions of S, Cℓ, Ar, etc.; b) we can use theoretical models embracing all relevant physics of ionization and recombination, charge exchange, radiative transfer, and include complications introduced by condensations, dust, etc. The beautiful model by Harrington et al. (1982) for NGC 7662 shows an approach that is rigorous, elegant, and well suited to symmetrical PN for which detailed observational data exist. I believe it is the method of the future; c) we can use theoretical models as interpolation devices. We fit certain line ratios as closely as possible, notably 4686/4471, He II/He I, 3727/4959 + 5007 [O II]/[O III], 3426/3868 [Ne V]/[Ne III] and then adjust abundances to represent line intensities as well as we can, thus obtaining "model" abundances. Also, we can use the models to get ionization correction factors (ICF's) and apply them to get "extrapolated" abundances. The two techniques give log N(X)'s differing normally by about 0.1. Our team applied this procedure to study some forty-odd PN. For most of them, application of the Harrington et al. procedure would have exceeded our computing budget. Limitations imposed by geometrical irregularities and big density fluctuations are assuredly real, but we believe that by starting with the best physics we can, and later introducing modifications imposed by dust and blobs, we can approach accurate results asymptotically.

Table 1 shows some mean results, obtained primarily by models. These data refer mostly to relatively bright, nearby PN (Aller and Czyzak 1982). The assignment of population types was taken from Kaler (1978). High-excitation objects are those for which λ4686 He II of nebular origin is certainly present. Nitrogen-rich objects are defined as those with log N(N) > 8.0; carbon-rich objects are those with C/O > 1. The He/H ratio tends to be larger in N-rich PN, as has been noted by Peimbert (1978) and by Kaler (1978). Elements heavier than He are less abundant in Population Type II PN than in those of Population I. Ne, S, Cℓ, and Ar seem to have similar abundances in Population I, high-excitation, C-rich, and N-rich objects. C and N show considerable fluctuations as has been noted by many workers (e.g., Peimbert, Kaler). Comparisons with solar abundances show some close similarities but also conspicuous differences. In contrast to Kaler's (1981) conclusion, we find the C/O ratio in PN to be generally higher than in the sun. Although there is a tendency for the mean value of the C/O ratio found from λ4267 to exceed that from the UV lines, log <C/O> [4267] - log <C/O> [UV] ~ 0.16, there seems to be a large intrinsic spread (>> 0.16 dex) in the C/O ratio, no matter whether we use recombination or collisionally-excited C lines. Oxygen appears to be less abundant in PN than in the sun. Peimbert and Serrano's (1980) value, log N(O) = 8.83, was obtained with a temperature fluctuation parameter $\Delta\tau^2$ = 0.035.

Table 1. Mean Logarithmic Abundances (Mostly From Models)

	Pop. I	Pop. II	High Excitation	N-rich	C-rich	Solar
He			11.04	11.3.	11.03	11.0:
C	8.82	8.72	8.89	8.50	8.99	8.65
N	8.12	7.94	8.39	8.88	8.15	7.96
O	8.68	8.58 K	8.66	8.71	8.69	8.87
Ne	8.08	7.88	8.02	8.05	8.05	8.05
S	6.96	6.88 K	7.03	6.98	7.09	7.23
Cℓ	5.28	5.13	5.27	5.4	5.27	5.5
Ar	6.42	6.22	6.48	6.65	6.46	6.57

See also Peimbert and Serrano (1980); Kaler (1978, 1980); Dinerstein (1980); Beck et al. (1981); French (1980). Solar values are those presented at a 1980 Santa Cruz workshop, these come from Lambert (1978) and Ross and Aller (1976). In high-excitation planetaries, the following logarithmic mean abundances were found: F (4.6), Na (6.18), K (5.0), and Ca (5.0). K denotes values from Kaler (1980).

Distinctive composition anomalies are well known in halo PN. The He/H ratio is essentially cosmic, but big differences occur in other elements, the most dramatic effect being in Ar which Barker (1980) finds to be about two orders of magnitude less abundant than in general field PN. Galactic bulge PN merit more study. Do they have "normal" compositions (Webster 1976) or do many have high O/H ratios as Price (1981) found for H 1-55? Chemical composition gradients in disks of galaxies are well-known from studies of H II regions. Many attempts have been made to use PN for this purpose in our galaxy (D'Odorico et al. 1976; Aller 1976; Barker 1978; Peimbert and Torres-Peimbert (PTP) 1977; Kaler 1978; Peimbert and Serrano 1980). The derived gradients depend on the selection of objects and the size of the temperature fluctuations that are assumed. C and N are manufactured in the PN themselves and cannot be used to obtain galactic composition gradients unless one can clearly separate those PN whose progenitors have manufactured C and N in their interior from those that did not. More massive stars, which presumably evolve into the brighter PN, certainly produce C and N. Peimbert and Serrano (1980) suggested that N-rich stars that enrich the ISM with He and H constitute 20% of the total. In classifications by Acker (1980) and by Kaler (1980), two distinct groups are discussed. One includes relatively young PN (age $< 10^9$ years), many with high Ne and N enrichment, and presumably more massive progenitor stars; they seem to be essentially Population I objects moving close to the galactic plane in orbits of low eccentricity. The other group includes old PN (ages up to 10^{10} years), small He or N enrichments; these are old disk PN plus some halo objects (in Acker's group). They move in more elliptical orbits and often show lower excitation (Kaler 1980).

Theories of the late stage of stellar evolution (Paczyński 1970; Renzini and Voli 1981; Iben and Renzini 1982) predict the enrichment of certain chemical elements in outer stellar envlopes that are destined to be ejected as PN shells. As the star evolves up the AGB, the mass M_e above the H-burning shell decreases because H is converted to He at its base and sinks into the core, while the upper part is lost in wind. At some point this outer envelope is ejected. It may form a dense, dusty shell that temporarily hides the core which eventually settles down to become a white dwarf. Paczyński's and subsequent theories have predicted that the more massive the core, the faster it fades. Calculations of advanced stages of AGB evolution as a function of progenitor star mass give L, T_{eff}, and dM/dt and also surface abundance ratios, He/H, C/O, and N/O as functions of time. Detailed results depend on the initial He/H ratio and on the ratio of mixing length to scale height.

Figures 1, 2, and 3 show the predicted and observed relationships; C/O versus He/H, N/O versus He/H, and C/O versus N/O. The He/H ratio should be good to ~ 0.01; the log C/O ratios may have uncertainties of ~ 0.2 to 0.3, while the N/O ratios should be more accurate for most objects. The detailed results differ slightly from those of Peimbert (1981) since different data are employed here. He concluded that the ejected shell had a smaller mass than the predicted one, that the He enrichment could be explained if the PN originated from stars in the 1 to 5 solar mass range, and that N enrichment exceeded predicted values. Note that the theoretical curves can be shifted leftward in Figs. 1 and 2 by changing the initial He content of the progenitor stars. Masses of progenitor stars are indicated by numbers in [ ] brackets and tick marks on the curves. Although the ordering of successive masses is correct, one cannot guarantee that exact locations are accurate; the whole system of tick marks may have to be displaced up or down along the curves. Most of the PN would appear to have come from progenitors of less than 3 solar masses; Hu 1 - 2 and NGC 6778 may have come from more massive stars. The N-rich object NGC 6302 (Aller et al. 1981) has a higher He/H and a lower C/O ratio than theory suggests. C and perhaps O were processed to N and excess He was produced in a vigorous CN cycle operation. Also, C may have been preferentially converted to N in the progenitors of Hu 1 - 2, NGC 2440, 6741, and 6778. Note that IC 351, 4593, and 4634 seem N weak. The N-rich object in NGC 6822 (Dufour and Talent 1980) may be similar to NGC 6302, or even a more extreme example.

Although much of the scatter in Figs. 1, 2, and 3 may come from observational uncertainties, some deviation seems real. Some PN do not follow the prescribed scenario. Improved stellar evolution calculations and abundances are both needed. In Schönberner's 1981 model, where m(residual core) = 0.58 for all PN, it appears difficult to find dredge-up mechanisms that can give such a variety of chemical compositions. Who knows? PN composition investigations may yet help dredge-up theory.

Additional insights are offered by PN in other galaxies, although observations can be difficult. Particularly noteworthy are the measurements by H.C. Ford and associates of O/H gradients from PN in M 31, and PN detection in the Virgo group. So far, a relatively small number of objects has been studied in the Magellanic Clouds. Comparing their results for seven PN in the SMC with analyses of H II regions, Aller et al. (1981) found He/H and N/H to be enhanced by factors of 1.2 and 5, respectively, although the abundances of O, Ne, S, and Ar seemed consistent with H II region data.

Table 2 compares data for eight PN observed in the LMC from Cerro Tololo. Except for P40, simple approximations have been used to get N(X) from $N(X_i)$. For Ar we observe most of the ionization stages but for S, I have employed the approximation $S/O = (S^+ + S^{++})/O^+$; the resultant, highly uncertain numbers are placed in [ ]. More accurate values must await proper models, but results for He, N, O, Ne, and Ar ought to be good to a factor of about two and enable us to draw some conclusions. For comparison, log N_{el} for LMC H II regions from models by Dufour et al. (1982) and Aller et al. (1979) are He: 10.93; N: 6.98; O: 8.41; Ne: 7.73, S: 6.96; and Ar: 6.24. P07, P08, and P38 are He rich (Webster (1976); N is enhanced in P07 and P08 by about a factor of 36 over LMC H II regions. For the other PN, the factor is about 5. To within the accuracy of the analysis, log $\langle N(PN)\rangle \sim$ log $\langle N(H\ II)\rangle$ for O, Ne, and Ar. Notice the depletion of O in P7 and P9 where N is greatly enhanced, suggesting that O may have been converted to N. P25 shows prominent lines of [Ar V], [Ne IV], λ4724, 26 [Ca V], [Fe V] λ4227 and probably [Fe VI] and [Fe VII] as well; O is depleted with respect to the local ISM, but N is enhanced. Is P25 a PN where Fe isn't locked in grains? We do not know the proper mix of N super-rich and N less-rich objects, so we cannot yet estimate how important PN are as suppliers of N, but there can be no doubt that they are copious sources of C. IUE observations by Maran et al. (1982) show the C enhancements to be spectacular. Carbon is about 40 times more abundant in the SMC PN than in SMC H II regions, with a corresponding ratio of about six for the LMC. In fact, the C abundances are comparable with those found in galactic PN, suggesting that the process of C synthesis and subsequent dredge-up are the same in PN progenitors, whether they be in the galaxy, the SMC or the LMC. Exploring yet further, the Fornax PN is also found to have C/O > 1 (Stecher et al. 1982). I want to emphasize that in each instance we are observing intrinsically bright PN; reaching fainter objects will be difficult.

At the 1977 conference, Terzian enumerated some unsolved PN problems. Many remain unresolved but progress occurs. We can now attack Minkowski's apparent paradox of the fast PNN wind as contrasted

Table 2. Logarithmic Abundances in Planetaries in the LMC

Element	P02	P07	P08	P09	P25	P33	P38	P40
He	11.06	11.20	11.03	11.23	11.04	11.08	11.176	11.02
N	7.83	8.53	----	8.55	7.24	7.68	7.74	7.5
O	8.26	8.04	8.46	8.02	8.07	8.43	8.40	8.33
Ne	7.65	7.61	7.67	7.54	7.56:	7.69	7.62	7.62
S	[7.35:]	[7.26:]	[7.9:]	[7.66:]	[7.11:]	[7.35:]	[7.51:]	6.42
Ar	6.06	6.23	>5.8	6.32	6.11	~6.4	6.84:	6.19

with gentle PN expansion rates. Low mass loss rates, $10^{-8} < \dot{M}\ 10^{-7}$ m(sun)/year Perinotto *et al.* 1982; Castor *et al.* 1981) can't explain the detachment of PN shells, although 1500 to 2000 km/sec winds might affect the excitation of some spectral lines in PN.

Great advances should be coming in PNN studies, e.g., checking Paczyński's relation between mass and fading time for progenitor stars. UV observations can help us check theoretical models of stellar fluxes, derive $T_{eff}(^*)$ and log g. Pottasch (1981) suggested large masses and high T_s's for a number of PNN. The notorious discordance between $T_{Zanstra}$ and T_s inferred from dark-line spectra of some PNN warns us against simplistic stellar atmospheric models. Planckian fluxes are outmoded; we must allow for stellar coronae and chromospheres. Another clue to T_s is given by flux distribution needed for excitation of an observed nebular spectrum, e.g., for the PNN in NGC 7662, $T_s \sim$ 95,000°K. To apply this method extensively, we need a fine-grid network of stellar models.

To improve our statistics, we need Hβ fluxes, spectra, A_V, and PNN data for many more objects. More information is needed even for traditional PN, e.g., accurate isophotic contours are necessary to interpret PN spectra. Most of the discordances in line intensity measurements arise not from a lack of precision in the same, but because different measurements, photoelectric, ptg., and ITS refer to different places in a PN image. The effect is especially bad in PN like NGC 6720 or 7009, where large excitation differences occur on a small spatial scale, and for comparing IUE and optical data.

The space telescope can give us monochromatic images for tantalizing PN like NGC 7027 or 2392, resolve the structure of PN in the Magellanic Clouds, and yield statistics on PN in the Virgo cluster.

Theoretical problems run a gamut from atomic physics (Ω's, A's, charge exchange cross sections), molecular structure and "dirty" chemistry (including grain formation and binding of Ca, Al, Fe, etc., in solid structures), the complete hydrodynamical structure and history of a typical PN, to the details of the last active chapter of stellar evolution. Our work is laid out for us!

Illustrations

1) Comparison of Log n(C)/n(O) With the He/H Ratio. The solid curve gives Renzini and Voli's prediction (1981) for their parameter α = 2, the dotted curve for α = 1.5. The numbers in brackets indicate the initial masses of the progenitor stars, 1.0 to 5.0 M(sun). The more accurate determinations are indicated by solid dots, the less accurate ones by open circles.

2) Comparison of Log n(N)/n(O) With the He/H Ratio. Notation and symbols are as in Figure 2.

3) Comparison of Log n(C)/n(O) With Log n(N)/n(O). The notation and symbols are as in Figure 2. Compare Peimbert (1981).

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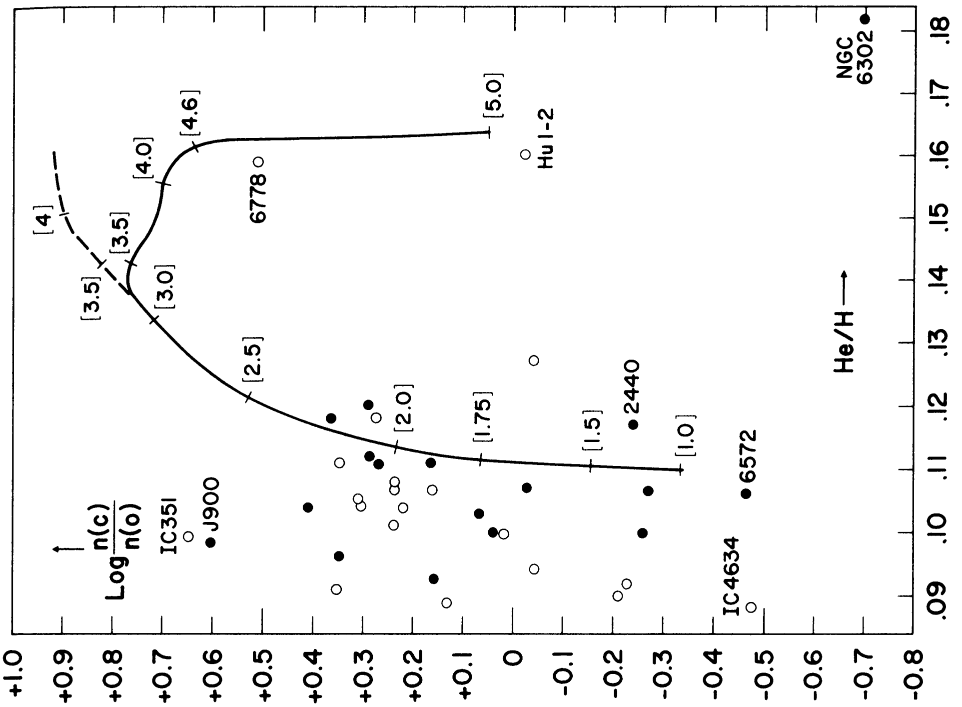
Log n(c)/n(o)
He/H →
+1.0
+0.9
+0.8
+0.7
+0.6
+0.5
+0.4
+0.3
+0.2
+0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
.09
.10
.11
.12
.13
.14
.15
.16
.17
.18
[4]
[3.5]
[3.5]
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[1.75]
[1.5]
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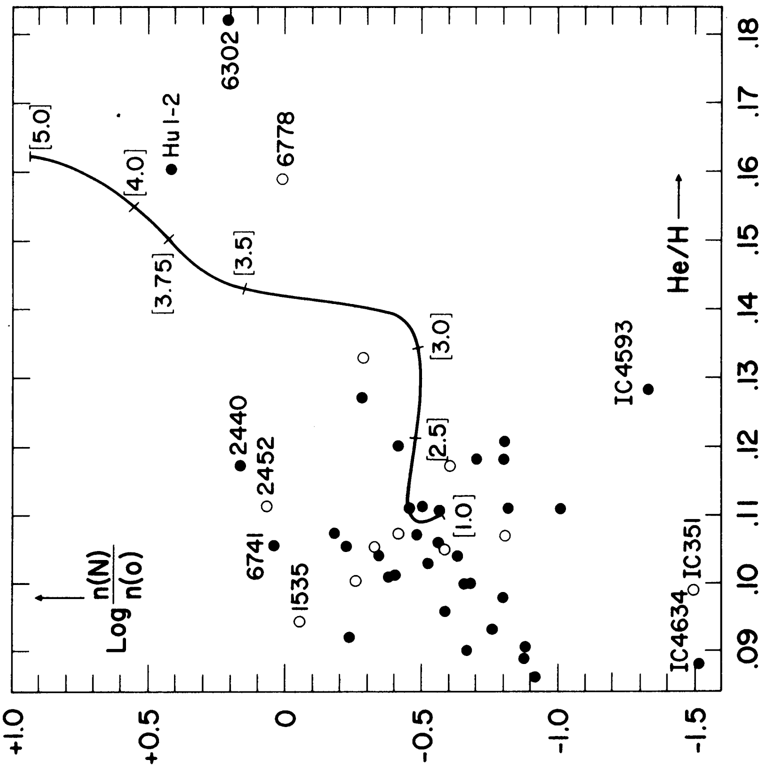
IC351
J900
6778
Hu1-2
2440
6572
IC4634
NGC 6302

Fig. 1


Log n(N)/n(o)
He/H →
+1.0
+0.5
0
-0.5
-1.0
-1.5
.09
.10
.11
.12
.13
.14
.15
.16
.17
.18
[5.0]
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[3.0]
[2.5]
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6302
Hu1-2
6778
2440
2452
6741
1535
IC4634
IC351
IC4593

Fig. 2

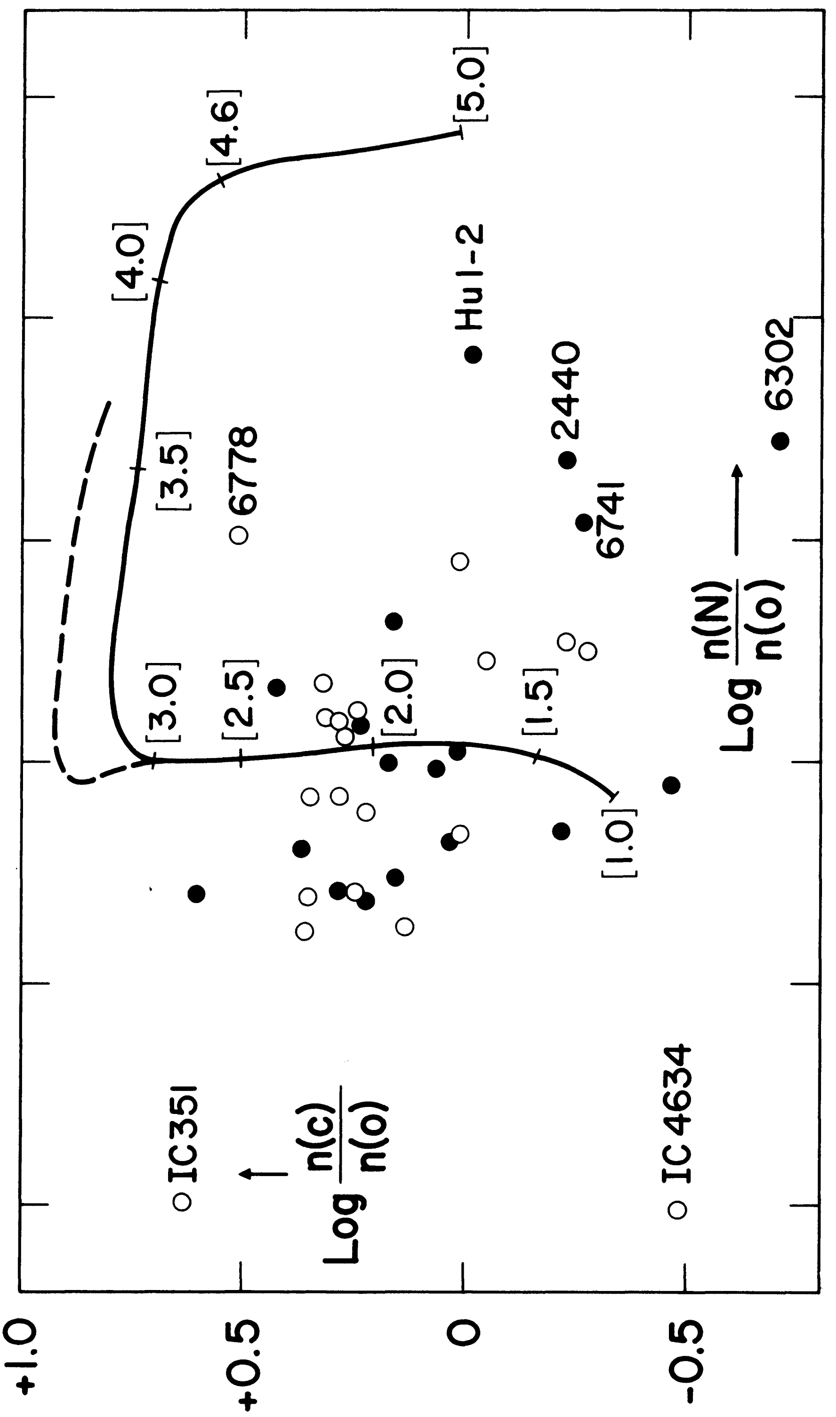
+1.0
+0.5
0
-0.5
-1.0
-1.5
Log n(N)/n(o)
+1.0
+0.5
0
-0.5
Log n(c)/n(o)
[1.0]
[1.5]
[2.0]
[2.5]
[3.0]
[3.5]
[4.0]
[4.6]
[5.0]
IC351
IC 4634
6778
Hu1-2
2440
6741
6302

Fig. 3

OSTERBROCK: Are any elements with higher Z than Fe observed in any PN shells?

ALLER: Beyond the iron peak, the abundance curve declines rapidly so it is not surprising that lines of these elements have not been seen. There is also a tendency for the iron group elements to be tied-up in grains, as Shields has pointed out.