SUMMARIZING REMARKS ON THE STRUCTURE AND EVOLUTION OF PLANETARY NEBULAE AND PROPERTIES OF THEIR CENTRAL STARS.

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To review or attempt to summarize a conference such as this recalls the request our department office once received from a little fourth-grade schoolgirl: "I'm doing a science project on the stars. Tell me all about them on two pages." We can only try to look at the broad picture and attempt to identify problems that require special emphasis or attention.

First of all, I'd like to remark on the wide geographic distribution of planetary nebulae enthusiasts. In addition to capable, well-organized and well-led groups at larger centers such as Groningen, London, and Mexico City (to mention only three), there are outstanding investigators at many other places, for example in South America and India. One has only to glance at the bibliography of the new comprehensive planetary nebular catalogue by Acker et al., — a truly formidable undertaking — to appreciate this point. Like the whole science of astronomy, PN research is an endeavor in which the whole world can rejoice.

Impressive advances have been made both in theory and observation, the latter providing foundations for the former. New technologies now permit definitive attacks on a broad range of problems. Developments in CCD's make possible quantitative monochromatic direct imaging of PN as illustrated by the beautiful pictures shown to us by Bruce Balick, Ms. Chu, J. Jacoby and associates, by J. Lutz, and many other participants, particularly in the poster sessions. Applications to high-dispersion spectroscopy as in the outstanding survey of the infrared spectrum of NGC 7027 by D. Pequinot and R.B. Gruenwald and the remarkable echelle spectra of planetary nebulae nuclei (PNN) by J.K. McCarthy are two examples of the power of new techniques that will open inspiring vistas to PN investigators. These CCD detectors also enable the enthusiast for nebular kinematics to detect heretofore unknown speedy blobs in many nebulae.

IRAS data, described by A. Preite-Martinez constitute one of the truly great leaps forward in PN study. The survey covered 98% of the sky from 8 to 12 μm. Alas, NGC 7027 was missed! The survey provided energy distributions for 70 PN, low-resolution spectra (LRS) for 60 PN, and detailed maps for three large objects, including NGC 7293. These

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IRAS data proved fundamental for determinations of temperatures, energetics, and spatial spread of dust. It also detected halos at $\lambda > 50$ μm. IRAS supplied very important abundance information for Ne, S, and Ar, whose ions have heretofore been observed with difficulty from the ground. Spatial distribution of [O IV] in NGC 7293 has been measured. Much more information remains to be extracted from the IRAS tapes. Preite-Martinez and Pottasch estimate that more than 500 objects, both PN and proto-PN, observed in the far-IR, remain to be confirmed with radio and near-IR observations.

As IR arrays are developed and applied to PN problems we can make detailed maps of the dust distribution and compare them with maps made in the radio-frequency (r.f.) domain which shows the H+ gas distribution. Roche noted that by comparing images of Brackett and of dust in nebulae such as BD + 30°3639 and NGC 7027, one finds that the dust and gas do not peak in exactly the same places. In NGC 7027 the dust peaks just outside the H+ region although some must exist therein. Nebular images in hot dust can be found in NGC 7027, but we need to know where the cool dust that radiates in the 30- to 100-μm region is located.

With the VLA, Terzian notes that it is possible to construct r.f. isophotic maps with a resolution between 0.1 and 1.0" not only in the H II (H+) continuum but also in H I (observed in NGC 6302, IC 418, and IC 4997) and in the OH 1612 Mhz maser line seen in Vy 2-2 (a very young PN) and in NGC 6302. Important progress is being made in studying the transition from OH-IR stars through the pre-PN phase. Terzian reports that first epoch observations have been secured for measurements of expansion velocities in a number of PN; these may prove useful in handling the troublesome problem of nebular distances.

Thus, we now can obtain PN images in the radiations of H, lines excited by collisions, molecules and dust which may emit over a wide range of temperatures and densities. Supplementing these data are kinematical measurements. We obtain line-of-sight velocities over the nebular surface and eventually the proper motions of knots and filaments across the line of sight.

Balick summarized the structures and morphologies of PN as revealed by CCD direct imaging. Most of the mass destined to form the PN was ejected in the slow wind, but the topology was later largely fixed by the fast wind (~ 2000 km/sec) emerging from the central core remnant. This scenario, proposed by Sun Kwok, seems well established as a basic working hypothesis. Balick emphasized that the actual appearance of the nebula depends on the age or stage of evolution of the nebular shell and the configuration of the ejected material. If the ejected shell is spherically symmetrical, we observe a structure such as IC 3568 or an annular nebula such as NGC 6894. More often the shell is not spherically symmetrical but is thicker and/or denser in the equatorial plane so the outrushing wind bursts through in the polar regions first. For a detailed summary, see Balick (1986).

The next step is to build numerical models where the history of a PN can be followed by two-dimensional hydrodynamics with radiation pressure taken into account. Kahn sketched some possibilities involved, suggesting that the superwind might be nonsymmetrical.

Detectable effects on PN shapes might appear in 10 to 400 years. The shapes of PN are fashioned by winds and radiation pressure but the ionization and heating of the detached red giant shell is due to the stellar radiant flux. In bright rims, we might observe sometimes the dissipation of energy from winds. Before detailed modeling can be undertaken, we need improved, high spatial resolution observational material from the r.f. to UV regions with supplementary kinematical data to match. Velocity patterns must be measured over the entire PN image; O.C. Wilson tried this long ago with a multi-slit; Fabry-Perot interferometers are now often employed.

Multiple shells are common phenomena in PN. Ms. Chu finds that 50% of nearby objects in the NGC and IC catalogues have multiple shells. Kaler had classified them on the basis of their surface brightnesses: I = faint detatched shells that show limb brightening and with outer diameters exceeding 0.5 pcs. The masses are low (~ 1%) compared with the inner bright ring. Type II shells have an attached outer ring that is about 25% as bright as the inner ring. These shells have radii less than 0.5 pcs, show no limb brightening, and have masses comparable with that of the main ring. Some objects such as NGC 2392 are classified as "peculiar." The motions can be complex and follow no uniform pattern. Ms. Chu notes that sometimes the attached outer ring co-expands supersoniocally with the inner shell, suggesting a possible multiple ejection. Other times a supersonically moving inner shell collides with a faint, subsonically expanding halo. In PN such as NGC 6826, a slow moving inner shell penetrates a faint outer one.

In M2-2, however, a detached outer shell expands independently of the inner shell. Different formation mechanisms are clearly involved. Curiously, elemental abundances in the outer shells usually did not differ from those found in the inner shells. Tylenda's suggestion that a faint outer halo may be a fossil ionized sphere left behind as the PNN fades certainly allows an observational test.

Weinberger's discussion highlighted the great complexity of the kinematical data. Unique, single-valued expansion velocities cannot be specified for individual objects. For example, it is not possible to define a specific expansion-velocity versus radius relationship for PN. Instead, one has to describe an entire velocity pattern for each object, a point emphasized by Chu et al. (1984). Although average expansion velocities of the order of 20 km/sec for H I and [O III] seem to be found in the majority of PN that have been measured, it must be emphasized that within some objects, such as NGC 2392, 6302, 6537, 6543, 6826, and M2-3, there occur jets moving with velocities up to 100 km/sec or more. These kinematical phenomena must be revealing essential clues to the initial, almost certainly non-uniform ejection and acceleration mechanisms.

The nature of planetary nebular evolution lies at the very center of our concerns. Before the London meeting our ideas on this subject were rather general as many essential observational details had not yet been provided. Now the scenario seems to be well-defined. Important steps are described in the reviews by Habing, Knapp, Renzini, and Kwok, while Roche and Rodriguez have described important clues provided by dust and molecular data.

The precursors of PN are Mira stars (long-period variables) or other asymptotic giant branch (AGB) stars. These evolve into OH-IR objects that are essentially invisible optically; they emit in the IR and r.f. spectral regions. Large numbers of them were "fingered" by IRAS and then verified by r.f. observations of the 1612 MHz line of the OH maser. The PN and OH-IR objects seem to show the same pattern in velocity and galactic distribution. The OH-IR stars are presumed to evolve into proto-PN and eventually into young PN such as Vy 2-2. We might expect the number of pre-PN to be the order of 10% to 25% of the number of PN, to show color temperatures of the order of 130 K to 200 K, to be non-variable (unlike their Mira or youngest OH-IR predecessors), to show silicate features, possibly also CO or OH, and to possess no optical counterparts.

Not all OH-IR objects are expected to evolve into PN and some PN (such as the strongly C-rich nebulae) may evolve by a different route. The "standard" evolutionary scenario starts with a Mira star with a period between 250 and 500 days, a variation of about one magnitude in bolometric luminosity, and an expansion velocity of about 5 to 10 km/sec. The mass loss may be triggered by pulsations and fall between a rate of 10^{-7} and 10^{-6} solar masses/year. As their outer envelopes expand further and cool, the Mira stars evolve into OH-IR variables with periods between 500 and 1000 days and amplitudes of about 2 magnitues. They attain luminosities of the order of 1000 to 10,000 that of the sun and the mass loss rate increases to 10^{-5} or even 10^{-4} solar masses/yr in the slow wind of about 10 to 15 km/sec. This stage may last 10,000 years. The outer shell is finally detached; the dying AGB star becomes now a non-variable OH-IR source with a hot core concealed under a thick, dusty, circumstellar envelope.

The next stage is the appearance of a fast wind from the hot core with a velocity of 1000 to 3000 km/sec, but a low-mass loss rate of about 10^{-7} solar masses/yr. The rich UV radiation field of the hot core now ionizes the slowly moving shell of the defunct red giant and turns on the PN. In many PN, much of the intact, cool, outer AGB envelope is still there; it is revealed by solid grains and molecules such as those of hydrogen and CO. There are found in NGC 2346, 6302, 6720, and 7027. OH is detected in the neutral torus around the waist of NGC 6302. It is also found in Vy 2-2 and IC 4997. Intensive searches have revealed molecules in only a few PN. Why? Rodriguez estimates that in a typical PN, molecules would last only about 100 years. Why are they found in an aged object such as NGC 7293? Possibly some PN contain dense blobs that shield them from radiation.

Dust occurs within the H II regions of PN as well as in cool, neutral regions, which may show a considerable temperature range. Among the IR lines is the 9.7-μm silicate feature characteristic of O-rich material. In sooty clouds are observed the 11.2-μm band of SiC and the 3.3- to 13-μm feature attributed to C-rich grains and polycyclic aromatic hydrocarbons (PAH's). Sometimes O-rich envelopes are associated with C-rich central stars, but never vice versa. As a result of He burning to C, and subsequent mixing to the atmosphere, O stars become C stars, but there is no evidence of a C star ever turning into an O star.

Studies of PN chemical compositions, reviewed by Clegg, put some contraints on evolutionary models. Of particular importance is the C/N/O ratio. With respect to the Sun, PN tend to be O-deficient, while C and N are often enhanced in PN. The N-rich objects, Peimbert's type I (1983), are believed to originate from the more massive progenitors. Large numbers of PN show C/O > 1 and are believed to come most recently from C stars. Neon is probably not affected by nuclear reactions in stars, while S, Cℓ, and Ar must relfect the abundance pattern of what are loosely called "metals." Thus, their abundances reflect that of the interstellar medium (ISM) from which PN progenitors were formed. New, improved atomic data such as collision strengths for lines of [S II], [Cℓ III], and Ar IV] will yield improved abundances of the corresponding elements. Calculations of increasingly accurate models such as that by Clegg et al. (1987) for NGC 3918 are very valuable.

Perhaps the best candidate to the missing link between OH-IR sources and PN is Vy 2-2 = 45-2°1, described in poster papers by Clegg, Hoare, and Walsh, and by Faloma and Sabbadin. VLA measurements at 15 GHz show it to have outer and inner shell radii of 0.25" and 0.1", N_ε = 300,000 cm^{-3}, and T_ε = 11,000°K. With an expansion velocity of 10 to 15 km/sec, it appears to have a dynamical age of 1200 to 2000 years. Thus, it is an object younger than NGC 6572, BD + 30°3639, or IC 4997. We hope that even younger objects will be revealed by IRAS data.

Any discussion of the evolution of PN and PNN brings us back to the distance problem. Methods now frequently employed include the use of 21-cm H I absorption, the reddening of nearby field stars, and stellar winds. Eventually, expansion velocities measured with the VLA may be useful. Although progress has been made, as Ms. Lutz has described, we cannot pretend that the distance problem is in a satisfactory state. For a particular PN, errors ranging from 30% to a factor of 2 are often quoted. This uncertainty enters in all types of discussion. As an example, let me illustrate how errors affect a dependence of N(O)/N(H) on R (distance from center of the galaxy) for type II PN. Faundez-Abans and Maciel (1986) have recently discussed this problem. C.D. Keyes and I selected objects primarily on the basis of their kinematical properties. We relied on lists by Kaler (1970), Barker (1978), and by Heap and Augensen (1987). We assume the distance of the sun, R(sun), to be 8500 pcs from the galactic center. Chemical compositions obtained via theoretical models were generally employed.

Our purpose in showing this diagram is not actually to discuss log N(O)/N(H) as a function of R, 8.69 - 0.0156 R(kpc), but rather to emphasize uncertainties that certainly accrue from distance errors. These may be less than 1 kpc for nearby PN but could be a factor of 2 for nebulae at a distance of 4 kpc or more. There is also an error of the order of 0.1 dex in the N(O)/N(H) determination, largely a consequence of uncertainties in T_ε. It is likely that much of the scatter in the diagram must arise from errors in the input data. Errors in the distance scale frustrate efforts to make reliable estimates about PN formation rates. Using Cudworth's distance scale, J.P. Phillips finds the formation rate of PN to be 6.2 to 13 pc^{-3}/yr^{-1}.

The number of objects for which accurate distances can be found, PN in binary systems, in the galactic bulge, and in the Magellanic Clouds, is inadequate for most purposes. Few PNN are binaries, while for nebulae at great distances, essential information on structure and internal kinematics is not available.

For planetaries whose central stars show absorption lines, a powerful method of distance determination has been developed by Kudritzki and his associates. Long ago it was suggested that by comparing the absorption line spectra of PNN with those of type I population O stars one could determine both their effective temperatures and surface gravities, expressed as log g (Aller 1948; Wilson and Aller 1954). The effort failed for two reasons, the inadequacy of too-low dispersion photographic spectra and use of LTE atmospheres. By using high-dispersion spectra measured with CCD's and modern non-LTE atmospheric models, Kudritzki *et al*. have shown that the effective temperature can be obtained to an accuracy of 10% and log g to 0.2 dex. Since stellar evolution theory for PNN gives a relationship between log g and the effective temperature for which one does not need to know the distance, one can deduce the mass, M; with M and g known, R can be found. With R and the emergent stellar flux, one can predict the absolute magnitude of the star of known apparent magnitude and thus deduce its spectroscopic parallax. A check on the method is provided by applying it to a hot subdwarf in NGC 6397. It gave the same distance to this globular cluster as did conventional, well-established methods. Furthermore, the absolute magnitudes of the brightest PN in the sample match those found in the Magellanic Clouds. These results favor the Cudworth distance scale. Where they can be determined for individual PN, the distances found by the Kudritzki method are to be preferred.

The perplexing problem of Zanstra temperatures, reviewed by Kaler and discussed in posters by Henry and many others, is not yet completely solved. Although the Kudritzki procedure seems to give a reasonable interpretation of a star such as the He-rich nucleus of NGC 246, (T_{eff} = 130,000°K, log g = 5.71), troubles appear to abound for yet hotter PNN, e.g., the nucleus of NGC 7027, for which model nebular methods give $T(*)$ = 190,000°K (Pequinot and Gruenwald) but the PNN magnitude $m(*)$ = 17.7 (Walton *et al*.) implies $T(*)$ = 310,000°K. For NGC 2440, $T(*)$ = 350,000°K was found from $m(*)$ by Zanstra methods, while Shields *et al*. (1981) found $T(*)$ = 180,000°K by model nebular methods. Similar difficulties occur for NGC 6565 where Reay *et al*. (1984) found T_Z(H I) = 185,000°K, T_Z(He II) = 130,000°K, while the level of the spectrum requires a $T(*)$ of about 85,000°K. One can scarcely account for these discordances by assuming that the PNN is fading rapidly; the response of the nebular spectrum easily would have been observed. Presumably, we must assume that if the star is as hot as indicated by Zanstra methods, heavy absorption must occur well shortward of 228 Å. Otherwise, [Ne V] would be predicted much too strong. These new theoretical stellar fluxes can help us in another important way. They provide excellent input data for the calculation of theoretical PN models so that we can concentrate on other matters such as geometrical factors in interpretations of nebular spectra.

Harrington emphasized the crucial importance of nebular geometry in his review of current developments in nebular modeling. Refinements in the basic theory as well as in the input atomic data are now available. Nebular modeling is becoming more and more popular; several codes are now used and intercomparisons between some of them have been made. In spite of refinements, small structural irregularities, knots, and condensations present difficulties. For example, when models are used to estimate ICF (ionization correction factors), large errors are possible as when we try to deduce the nitrogen abundance from [N II] lines. New trends in theory will include dynamical and evolutionary effects in a format applicable to individual observed objects. We hope theory will enable us to identify possible shock excited atomic transitions. Shocks are invoked to explain the shapes and forms of PN, but forecasts of observable spectroscopic effects are few.

The importance of stellar winds is clearly evident for many PN. For example, in constructing their model for NGC 1535, Adam and Köppen (1985) adopted $T(^*)$ from the work of Kudritzki et al., so they had to postulate a wind in order to explain the excitation level of the spectrum. Stellar winds can modify the far UV output flux; in some stars Kudritzki et al. found the $\lambda < 228$ Å flux to be enhanced by a factor of 1000! Grewing reviewed the general observed features of winds which blow with velocities between 500 and 4000 km/sec. As expected, all Wolf-Rayet-type stars show P Cygni profiles, as do many stars with bland spectra in the optical domain. Empirical or "observational" determinations or mass-loss rates depend on mechanisms invoked to produce and maintain these winds. Perinotto evaluated current popular theories and analyses based on P Cygni profiles observed with the IUE. He notes that the scatter in dM/dt for the same objects can extend over a factor of 100, but if we remove unnecessary discordances arising from various assumptions in fundamental parameters, this factor can be reduced to as little as 3 to 5, essentially the residual difference due to method employed. With the most recent version of a radiation wind-driven theory, it has been found that in the "best observed" PNN, NGC 6543, theoretical and "best empirical" dM/dt values differ by a small factor. Ultimately, we can hope to achieve an accuracy in dM/dt of a factor of 3.

Some of the main points in the theory of PNN evolution were already reviewed in 1982. Renzini and Schönberner gave an update, while Pottasch used a variety of distance determination options to compare an empirical luminosity versus T_{eff} plot with theoretical predictions. A number of objects near the galactic center seemed to depart substantially from the theoretical pattern, but the temperatures of these galactic center objects do not seem to be well determined. Using assumed initial mass functions and dM/dt rates for late AGB evolution, R.A. Shaw calculated some expected theoretical distributions of PNN in the logL - logT plane. These differed from the observations and suggested strong observational selection effects. Köppen emphasized the importance of linking PNN evolution with that of the PN itself and proposed some modifications or refinements of the Kwok two-stream model. In essence, dM/dt changes with time, perhaps increasing towards the end of AGB evolution as an OH-IR object, and possibly accompanied by Renzini's super wind.

PN with massive nuclei will evolve with a greater speed than "normal" PNN so that time-dependent effects should be readily observable. Such objects would attain high luminosities; yet, the upper limit of L(PN) seems rather sharply defined in other galaxies suggesting that there is no "high luminosity tail" in the distribution. We are not sure we have detected PNN with masses as high as 1.0 or even 0.9 m(sun). Tylenda suggests that NGC 2440, 6302, and 7027 may have large masses; NGC 6445, 6741, IC 2165, and M2-2 are other possible candidates.

Binary stars among PNN offer a number of unique opportunities to assess their masses and radii and to investigate possible effects of binarity upon nebular evolution. From his analysis of spectroscopic binaries, Mendez concluded that probably not more than 20% are close pairs, but if we allow for a range in masses and consider wider doubles, including eventual visual systems such as NGC 246, the percentage may be higher. A number of investigators have examined the possible role role of binarity in determining the shapes and forms of PN. J. Lutz and N.J. Lame secured monochromatic images of Abell 14, H3-75, and K1-2 with a CCD detector and concluded that the close binary character of their PNN may have influenced their structures.

In an excellent presentation, H.E. Bond noted that binary PNN are not freaks. Among the best known close binary systems are the nuclei of Abell 35, 41, 56, 63, and K1-2. Data for the best determined systems confirm that the stars are pre-white dwarfs and have masses of about 0.6 m(sun). Further clues to PNN masses are provided by the pulsations of the nucleus of K1-16. The pulsations involve a number of overtones so that evolutionary effects on the period are difficult to assess. Tutukov discussed the theory of close binary evolution. Can symbiotic stars evolve into PN? Can we acquire systems with a common envelope and can binary PNN evolve into cataclysmic variables?

What happens as PNN plummet to become white dwarfs (WD's)? J. Liebert reported that the low end of the PNN sequence and the high end of the WD region pose problems. The overlaps seem best defined by He-rich WD's and indicate a continuous sequence of stars from WC, OVI (or other He-rich, H-poor nuclei), through pulsating stars such as K1-16, field objects such as H1504+65 (which was discussed by Shipman), and finally the He-rich DO WD's, in decreasing steps of effective temperature. On the other hand, H-rich nuclei appear to evolve rapidly, but it is difficult to understand why hot DA stars are so rare. The PNN of NGC 7293 have appropriate values of (log g, T_{eff}) but this may be the only known example at this time.

Recently, a few very old, low-surface-brightness nebulae have been found around previously known faint blue stars. The best example is the hot DA, PG 0950+139, which is surrounded by a faint nebula discovered by Ellis, Grayson, and Bond. There is also a compact nebula (unresolved from the star) for which Liebert *et al.* find an electron density of the order of 1×10^6/cc, a mass of about 10^{-8} that of the sun and a radius of about 10 A.U. The star (log g = 7.5 T_{eff} = 70,000°K) has a cooling age of about 5×10^5 years; the faint nebula could have been ejected earlier.

Many excellent papers were well presented in poster sessions. It is unfortunate that the published volume can contain only abstracts which do not do justice to the wealth of high-quality data so often revealed.

In summary, new observational techniques and theoretical insights permit us to progress rapidly in the study of planetary nebulae. The importance of surveys is well recognized. We might have missed NGC 6751 with its engaging halo, which Ms. Chu has called to our attention. Many other examples exist. The Strasbourg catalogue is going to be of inestimable value to all of us working in this field.

At this epoch, however, a worthwhile undertaking might be to select a small sample of representative planetaries, preferably those whose distances could be established by the Kudritzki *et al.* methods. I would emphasize objects with well-established distances, for then we can express results in cgs, SI, or solar units. These objects should be observed intensively in the optical, IR, UV, and r.f. ranges with as high a spatial resolution as is practical. We could map images as observed in H, He I, He II, [N I], [N II], [O II], [O III], [Ne III], [Ne V], [S II], [S III], Ar III], [Ar IV], etc., and determine $\langle N_\varepsilon \rangle$, $\langle T_\varepsilon \rangle$, and velocity data point by point over the surface. Bits and pieces of such information exist already for many objects but the story must be put together more completely and the missing gaps filled in. By selecting candidates from young PN, such as NGC 6572, IC 4997, and BD+30 3639, to aged objects such as NGC 7293 and some Abell PN, we can provide challenging grist for the mills of the model builders and hydrodynamicists. We should also include "classical" PN such as NGC 40, 1535, 3242, 4361, 7009, 7662, and IC 418. We must not forget NGC 2392 with its intricate internal motions, for which Mendez *et al.* (1987) have deduced a PNN mass of 0.90 (which would imply rapid evolutionary changes) and an effective temperature of 47,000 K which is not consistent with its high excitation. In this PNN the UV flux from a wind must play a dominating role.

The record of firm accomplishments over the last half century is breathtaking. In 1937 I went to Harvard to work with Prof. Menzel. Very soon after my arrival he told me, "We are going to study planetary nebulae; they are very important."

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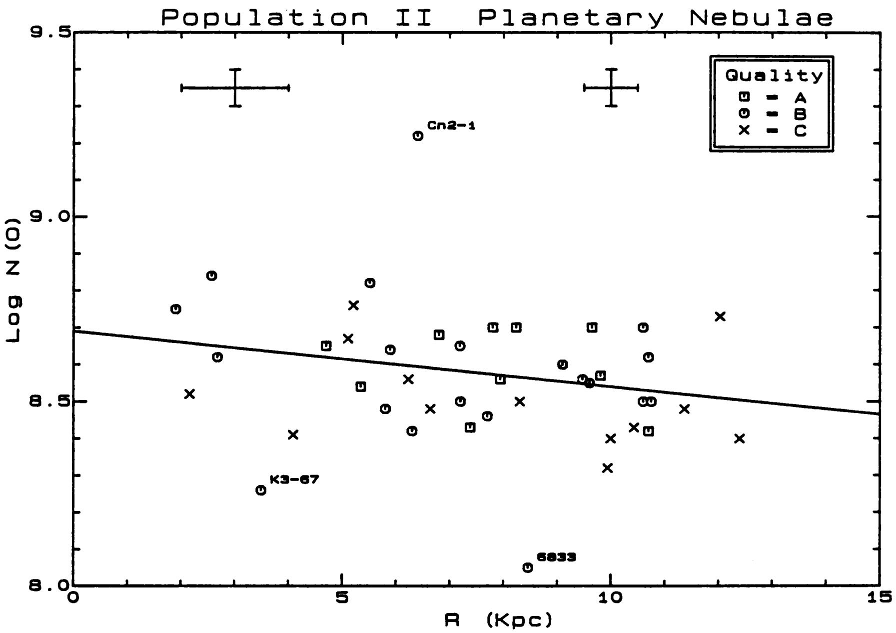

Figure 1. Oxygen/Hydrogen Ratio for Type II Planetary Nebulae.

We plot logN(O)/N(H) + 12 versus distance, R (in kpc), from the galactic center for population type II PN. Much of the scatter arises from observational errors in both distance estimates and abundances. The arrows give a rough estimate of the expected errors.