FINAL REVIEW

Yervant Terzian
Cornell University, NAIC, Ithaca, N.Y.

What splendid laboratories have planetary nebulae been! We have heard of important observations in the ultraviolet, optical, infrared, and radio spectral ranges, all rich in astrophysical information. We are now certain that planetary nebulae represent a crucial phase of stellar evolution. We have also begun to study the fine details of the evolution of planetary nebulae and our endless aim is to understand these objects completely.

The observational advances of planetary nebulae during the last few years have been dominated by the very successful 'International Ultraviolet Explorer'. Numerous important studies have been made at UV wavelengths, some examples showing the excellent UV spectra are shown in Figure 1 (compiled from Boggess et al. 1981). A classical example of an in depth study of a planetary nebula, NGC 7662, by Harrington et al. (1982) shows the vast and accurate information which can be obtained by combining the UV observations with optical, IR, and radio results. Figure 2 shows the UV spectrum of NGC 7662 and its decomposition into the stellar and nebular spectra, indicating a star with $T_S = 10^5$ K. The IUE has also produced some excellent high resolution spectra. The particular study of the CIII] λ1907/1909 ratio has proved useful for determining electron densities in planetary nebulae. Figure 3 shows several examples of the CIII] observations (Feibelman et al. 1980, and Feibelman et al. 1981). These high resolution spectra also indicate clearly the expansion of the nebular envelopes (NGC 3242, Hu 1-2). The theoretical computations for the line ratio λ1907/1909 as a function of density have been made by Loulergue and Nussbaumer (1976) and are shown in Figure 4.

Observational advances have also made possible the panoramic imaging of planetary nebulae in selected optical emission lines. Such studies have resulted in the determination of the electron temperature and density gradients in many planetary nebulae (Reay and Worswick 1982).

The remarkable optical spectrum of A30, shown in Figure 5, (Hazard et al. 1980, Jacoby 1979) has all the characteristics of a planetary

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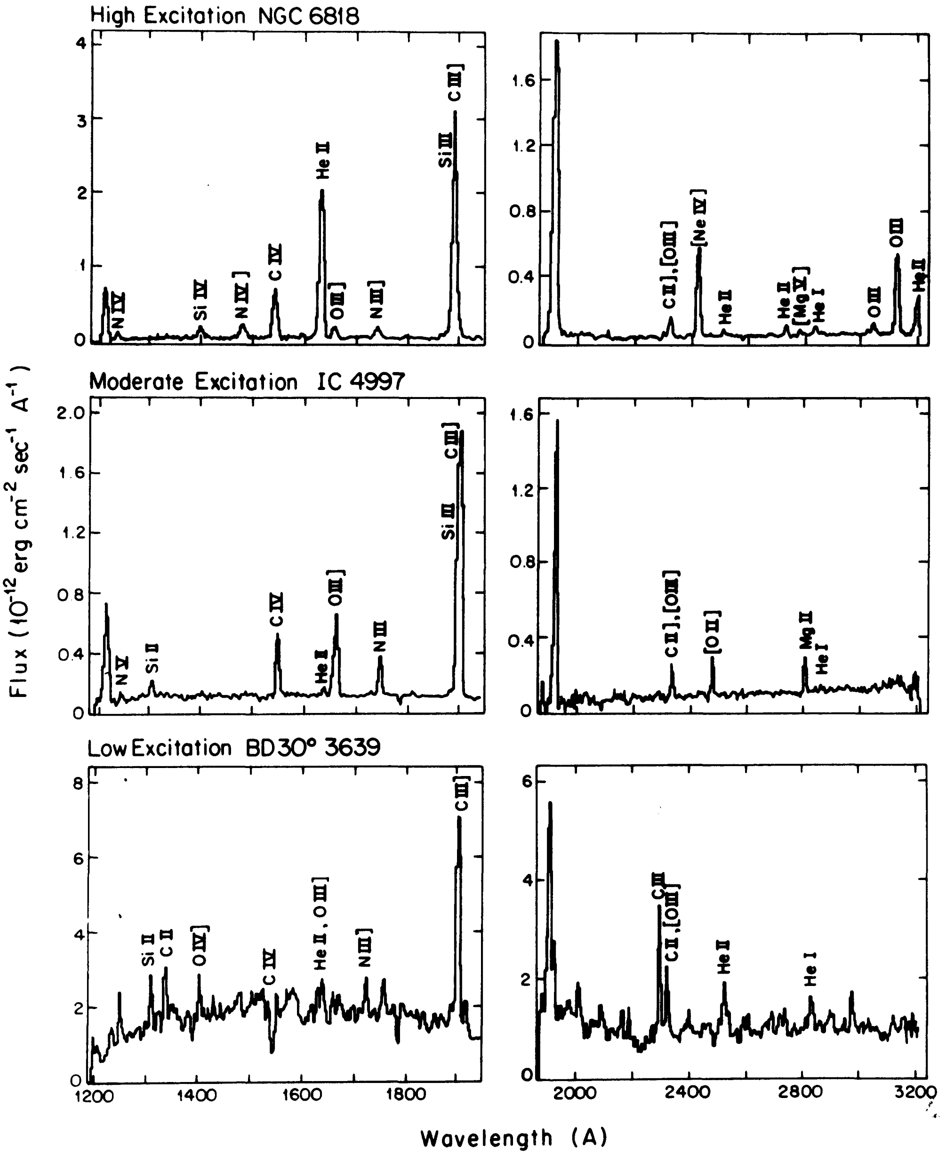


Figure 1. Three IUE representative spectra of planetary nebulae.

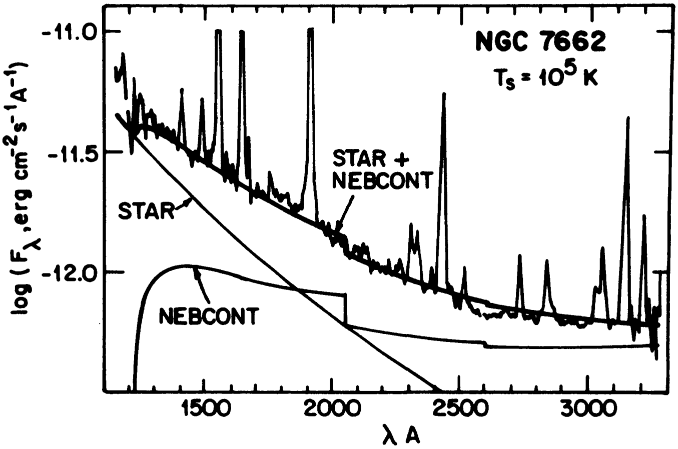


Figure 2. The ultraviolet spectrum of NGC 7662, where the stellar and nebular continua are also shown separately.

nebula except that it shows no Balmer lines. This may be due to material recently ejected from the central star, which may have been depleted of hydrogen due to previous explosions. Such new observational results are of primary importance for the study of the post red giant evolution, and in general for the evolution of the chemical abundances in the galaxy.

In the infrared spectral region the Kuiper Airborne Observatory has been used to study the infrared emission lines in many planetary nebulae. Recently accurate measurements of SIII at 18.7μ, NeV at 24.3μ, and OIV at 25.8μ, have been reported (Shure et al. 1982). Such information is essential for realistic determinations of the chemical abundances. High resolution observations in the infrared continuum have also been performed indicating the dust distribution in these objects. Most observations tend to indicate that the dust surrounds the ionized nebular gas, but there is some evidence that small amounts of dust may co-exist with the gas at the outer parts of the nebulae. It also appears that younger nebulae contain more dust and molecules compared to the older extended objects. There has also been some evidence of a size and temperature distribution of the grains.

In the radio spectral range the Very Large Array has begun to provide very high resolution radio images of planetary nebulae. Future observations with the VLA (and with the Space Telescope) will permit angular resolutions of ∿ 0.″1, which corresponds to 5×10^{-4} pc at a distance of 1 kpc. In many cases this resolution represents ∿ 1/200 of the size of the nebulae. Recent radio interferometric observations (Turner and Terzian 1982) with an effective resolution of ∿ 1" have already begun to study the compact 'stellar' planetary nebulae.

The technological advances which have permitted us to study planetary nebulae in the ultraviolet, optical, infrared and radio spectral regions have made possible a more complete analysis of the

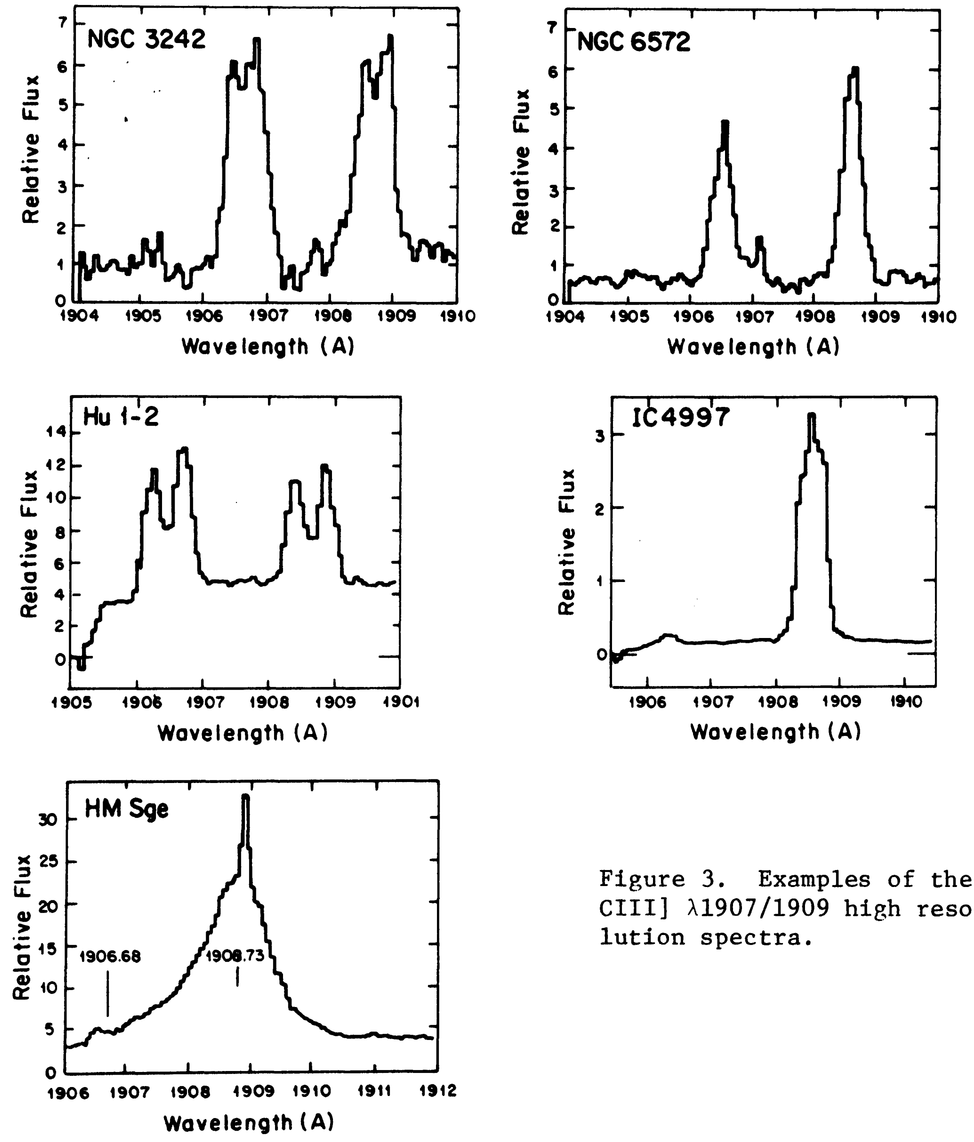


Figure 3. Examples of the CIII] λ1907/1909 high resolution spectra.

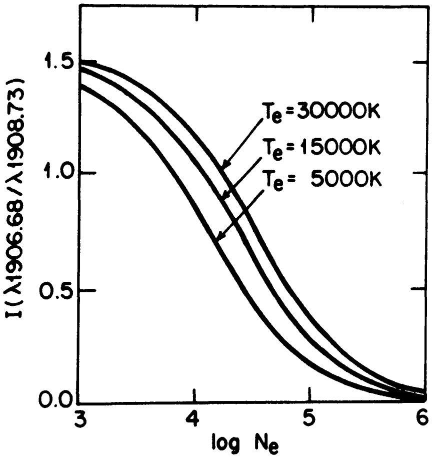


Figure 4. The theoretical line ratio for CIII] λ1907/1909 as a function of electron density for various electron temperatures.

excitation and ionization states of planetary nebulae, and in particular have allowed us to derive more realistic chemical abundances. Very recently Aller and Czyzak (1982) have completed a study of the chemical abundances of planetary nebulae and have concluded that pronounced chemical composition differences do exist in planetary nebulae, and that some are nitrogen rich and others are carbon rich. Nineteen different chemical elements have been detected in planetary nebulae, and abundance determinations exist for about 80 objects. There are however several outstanding problems including the marginal indications of abundance gradients in the galaxy, the very high He/H ratios (>0.18) determined for several nebulae, and the lack of a

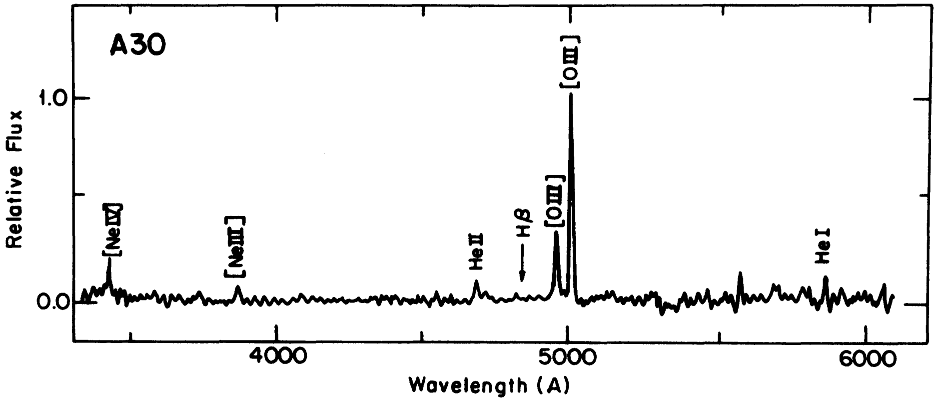


Figure 5. The optical spectrum of A30, note the absence of Hβ.

systematic study of abundances in halo objects. It is also remarkable that almost no attempts have been made to estimate the errors involved in determining chemical abundances, it is strongly suggested that such efforts be made in the future.

An important realization in the studies of planetary nebulae has been the possible large mass range of the progenitor stars from ~ 0.8 up to 6 or even 8 $M_\odot$. The mass distribution of the nuclei of planetary nebulae shows a strong peak at ~ 0.6 $M_\odot$, but extends slightly over 1 $M_\odot$. Therefore an important realization has been that the amount of ejected material back into the interstellar medium may be very substantial, and in some cases may be a few solar masses. It also appears that a large fraction of the ejected material is in a neutral state.

Mass loss from evolved stars and proto-planetary nebulae like IRC+10216, and CRL 2688 derived from CO observations (Knapp et al. 1982) show that $\dot{M} \sim 10^{-4}$ to 10^{-7} $M_\odot$/yr. Other nebulae show similar mass loses like NGC 7027, $\dot{M} = 4.0 \times 10^{-4}$; IC 418, $\dot{M} = 5.0 \times 10^{-6}$; and NGC 6543, $\dot{M} = 5.1 \times 10^{-6}$ $M_\odot$/yr derived from CO observations. The estimated mass of the molecular envelope around NGC 7027 is ~ 5 $M_\odot$, compared to 0.5 $M_\odot$ for the ionized mass. The mass of the central star of NGC 7027 is estimated to be ~ 1 $M_\odot$, resulting into a total progenitor stellar mass for NGC 7027 of 6 to 7 $M_\odot$. Recent UV studies of planetary nebulae nuclei (Heap 1980, Perinotto et al. 1981, Pottasch 1981) indicate wind driven mass loss inferred from the presence of P Cygni profiles in their spectra. This mass loss rate ranges from $\sim 10^{-6}$ to $\sim 10^{-10}$ $M_\odot$/yr.

The successful UV observations of planetary nebulae and their central stars in the Magellanic Clouds (Maran et al. 1982, Stecher et al. 1982) have provided additional information on the planetary nebulae stellar masses which are found to be ~ 1 $M_\odot$ from ~ 4 $M_\odot$ progenitor stars, hence indicating a mass loss of ~ 3 $M_\odot$ per star in various winds and explosions. And very recently Rodriguez and Moran (1982) may have detected a neutral hydrogen envelope around NGC 6302, indicating further that significant mass loss takes place from the progenitors of planetary nebulae (Figure 6).

The realization that the progenitor stars of planetary nebulae return a large mass fraction of processed matter back into the interstellar medium represents a fundamental conclusion. The chemical evolution of the galactic interstellar medium from light elements like H, and He into heavier ones like C, O, Mg, and Si is probably dominated by mass loss from the stellar progenitors of planetary nebulae. Since the rate of formation of planetary nebulae in the Galaxy is of the order of ~ 1 per year, then to a first approximation 10^{10} planetary nebulae were formed during the age of our galaxy, and perhaps 10^{10} $M_\odot$ of processed and perhaps reprocessed material has been provided to the interstellar medium.

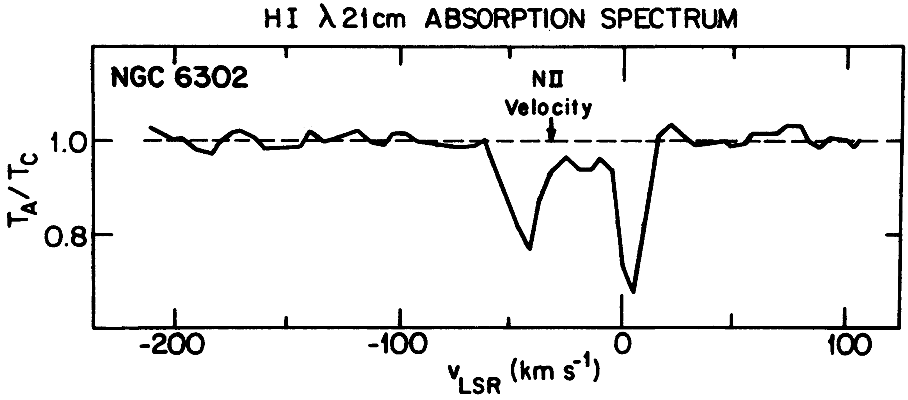


Figure 6. The λ21 cm HI absorption spectrum in the direction of NGC 6302. The arrow marks the nebular radial velocity from optical [N II] observations. The absorption at -40 km/sec may be due to the expanding HI shell of the nebula.

Careful and more sensitive observations of planetary nebulae have shown that many have double shells. More than half a dozen objects are now known with 'giant' halos (Terzian 1980). The mass involved in these outer halos must be significant - and probably is of the order of a solar mass or more.

There are now at least three examples of planetary nebulae with triple shells NGC 7009, NGC 7662, and NGC 6826. These objects have two inner shells and an outer halo. NGC 6826 recently discussed by Feibelman (1981) has an inner shell with a size of ∿ 10", and outer shell with a size of 25", and a halo 130" in size. Louise (1981) has also shown that on longer exposure photographs of planetary nebulae outer filamentary structure is normally seen. The length of photographic exposure seems to make great difference on what is observed. It seems likely that outer fainter halos around classical planetary nebulae may be common. This result has implications on the total mass ejected from the planetary nebulae progenitors, and possibly on the origin of the nebulae. Figure 7 shows the very symmetric bubble planetary nebula 268 + 11°1 (Longmore 1977), and the filamentary nebula Abell 43 (Jacoby 1982) for a morphological comparison. Figure 8 shows two nebulae with outer giant halos, NGC 6542 and NGC 6826 (Millikan 1974), note that the central images are overexposed in order to detect the outer fainter envelopes. Many other nebulae show predominantly a bipolarity in their morphological structure. This striking appearance is most obvious in the radio maps of these objects (Terzian et al. 1974) where the observed brightness distribution is not affected by

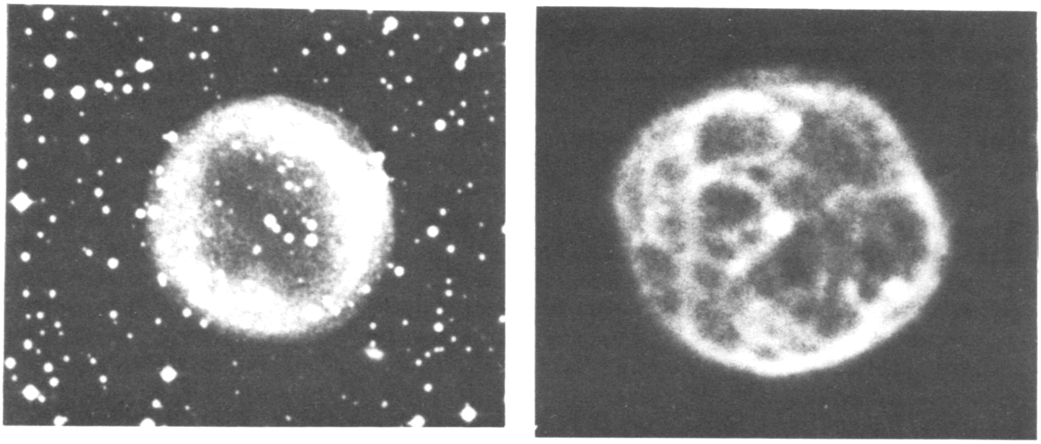


Figure 7. A symmetric nebula (286 + 11°1) and a filamentary (A 43 courtesy of Kitt Peak National Observatory) one.

dust. Figure 9 shows four bipolar nebulae with a striking resemblance (The Red Rectangle, M2-9, NGC 6302 and NGC 2346 courtesy of M. Cohen, L. Kohoutek, and R. Minkowski) strongly suggesting that some common physical processes govern the nebular ejection from their central stars.

The origin of planetary nebulae remains uncertain. Although sudden multiple ejections from a central star are suggestive due to the observed double and multiple shells, continuous mass loss and stellar winds have been given some attention (Kwok et al. 1978). Normal stellar winds however will not produce planetary nebulae, and a 'superwind' is necessary with a mass loss $\dot{M} \sim 10^{-5}$ to 10^{-4} $M_{\odot}$/yr. Figure 10 shows two examples of nebulae with double shells, NGC 2392 where the two shells seem to be detached, and NGC 3242 where no discontinuity is seen between the shells.

Five years ago during the IAU Symposium on Planetary Nebulae at Cornell University not a word was said on the importance of magnetic fields in planetary nebulae! Is it that we understand that magnetic fields are totally unimportant, or is it that we do not know how to deal with magnetic fields? Some have discussed that the bipolarity in the morphology of planetary nebulae has a natural explanation in the existence of a bipolar magnetic field, however no suggestions have been made as to how the field arises, and the required fields of $\sim 10^{-3}$ to 10^{-4} gauss are difficult to produce. Others, feel that the static magnetic fields do not contribute directly to the form and structure of planetary nebulae. It is perhaps possible that the stellar magnetic fields can influence the structure of the nebula at the very early

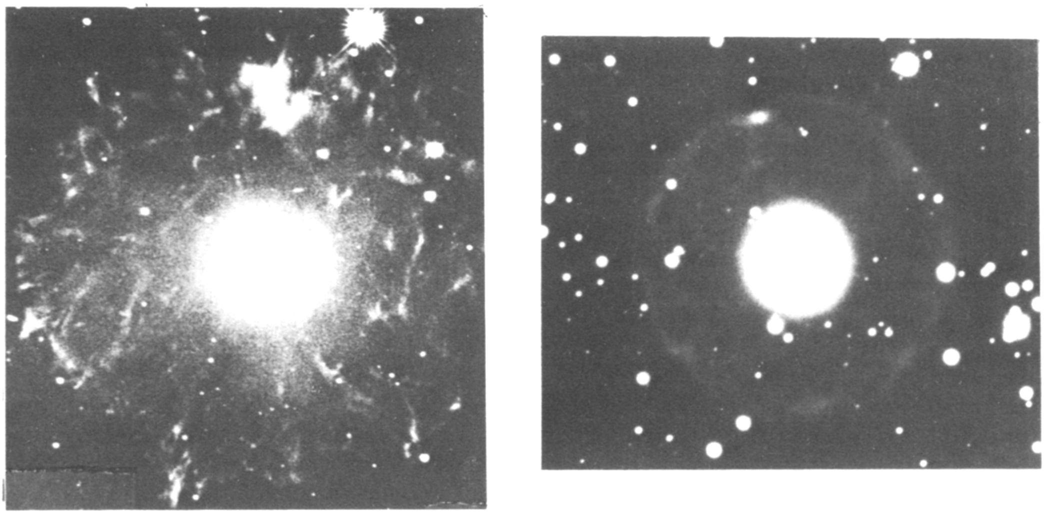
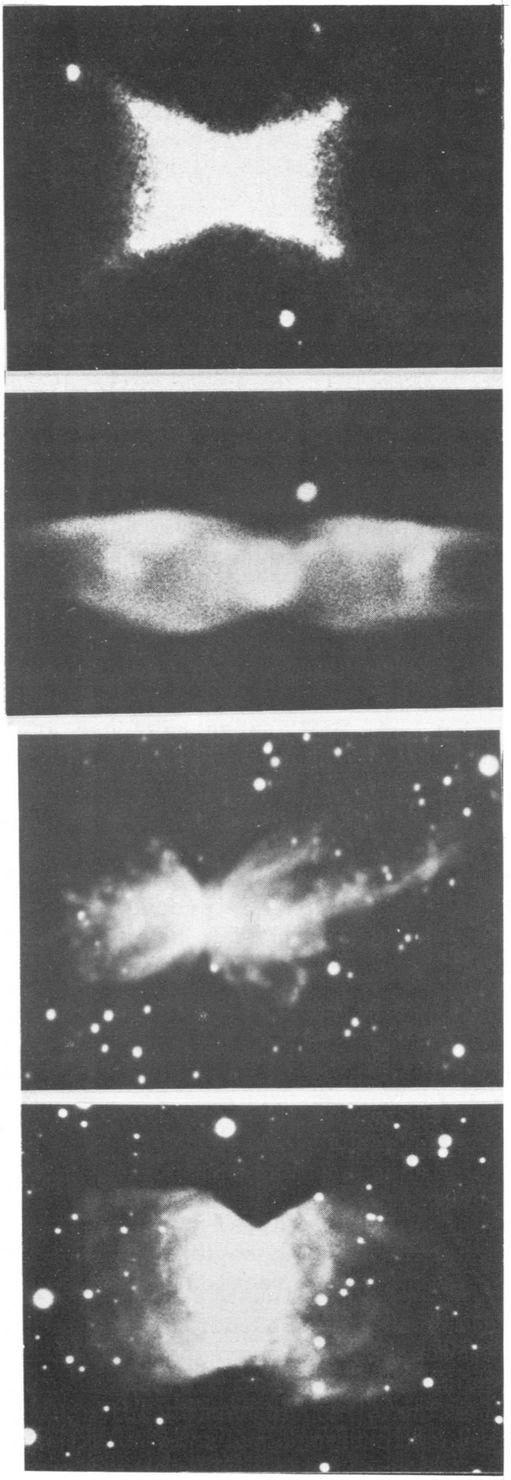


Figure 8. Giant halos around NGC 6543 and NGC 6826.

stages when the nebula is still part of the stellar expanded atmosphere. After ejection of the envelope the slowly expanding shell may retain part of its original structure. The problem of internal magnetic fields merits additional study. More recently Nussbaumer (1982) has suggested that magnetic flux, randomly emerging from stellar surfaces, may be responsible for certain types of stellar winds which may produce planetary nebulae. It is fair to conclude that we still do not have a fundamental understanding of the physical processes which produce planetary nebulae, and the explanation of the morphological types of planetary nebulae remains unknown.

Concerning the central stars of planetary nebulae there now exists a sample of 60 well observed stars which have a reported surface temperature range from $\sim$ 30000 to 350000K. There are however differences expressed by various authors in the physical parameters of the central stars and these should be resolved with further accurate observations. The existing theoretical model atmospheres of the central stars of planetary nebulae seem oversimplified and future work should concentrate in relaxing the assumptions, in particular a small fraction of metals should be introduced in the atmospheric composition.

It is encouraging to see that serious theoretical research is being performed on the gas dynamics of the nebulae. The prediction that the inner shocked stellar wind gas may be very hot with temperatures of the order of 3×10^6 K is an interesting new development and should be explored further.



It is also important to note that there now exist far better theoretical calculations on atomic parameters, although more work remains to be done. The construction of models has become standard practice for the interpretation of the nebular spectra and we have to ask if the physics is complete and accurate, and if the procedures are sound. We have seen, for example, that for realistic model one needs a density distribution in a gaseous nebula, rather than adopting a constant density.

Perhaps the most disturbing problem in the study of planetary nebulae has been the determination of the distance scale to these objects. Although some progress has been made by using a variety of distance determination methods, progress in this area has been slow, and individual distances may have errors of at least a factor of two. This situation makes it difficult to derive accurate luminosities, and also introduce a large error in the statistics and distribution of planetary nebulae in the galaxy. Nevertheless, the total number of these objects in the galaxy has been estimated to be about 28,00 with a local density of about

Figure 9. The bipolar nebulae The Red Rectangle, M2-9, NGC 6302 and NGC 2346, suggesting common physical processes for their ejection.

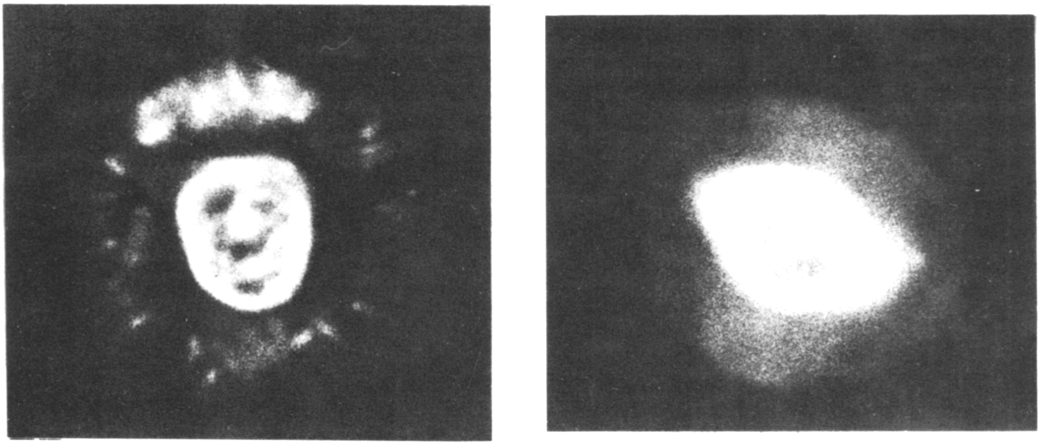


Figure 10. The detached double shell nebula NGC 2392, and the double shell nebula NGC 3242 where no discontinuity is seen between the shells (Palomar Observatory, California Institute of Technology).

50 nebulae within one kpc from the sun. The birthrate of these objects is ∿ 1 per year in the galaxy, however somewhat higher estimates have also been reported. The actual number of detected planetary nebulae in the galaxy is now about 1400.

Remarkable progress has been evident in the studies of planetary nebulae in nearby galaxies despite the very difficult observational task. More than 100 nebulae have been detected in each of the LMC and M31, and more than 50 in each of the SMC and M33. Preliminary results indicate an overabundance of C and N in these objects compared to our galaxy, and these important results should be examined more extensively.

It is clear that the classical picture of a planetary nebula as a hot bright and ionized envelope represents an oversimplified description. Today we have begun to understand the various stages of planetary nebulae from the red giant progenitor stars to the contracting white dwarfs. This evolution is rich in variations both for the central stars and their envelopes.

The next few years promise to be very fruitful in the study and understanding of planetary nebulae. The excellent recent theoretical work on the post red giant evolution, the formulation of model atmospheres of the nuclei of planetary nebulae, the stellar winds, the gas dynamics of the nebulae, and on the atomic data promise to yield a deeper understanding of the mildly explosive late evolutionary stellar stages of stars between 0.6 and a few solar masses.

On the observational scene the IUE work will be supplemented by optical observations with the Space Telescope, by infrared observations with the Infrared Astronomical Satellite and by radio observations with the Very Large Array.

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EDITOR'S NOTE: More recent computations of the C III line intensity ratio (Fig. 4 above) are to be found in H. Nussbaumer and H. Schild, 1979, Astron. Astrophys., 75, L17.