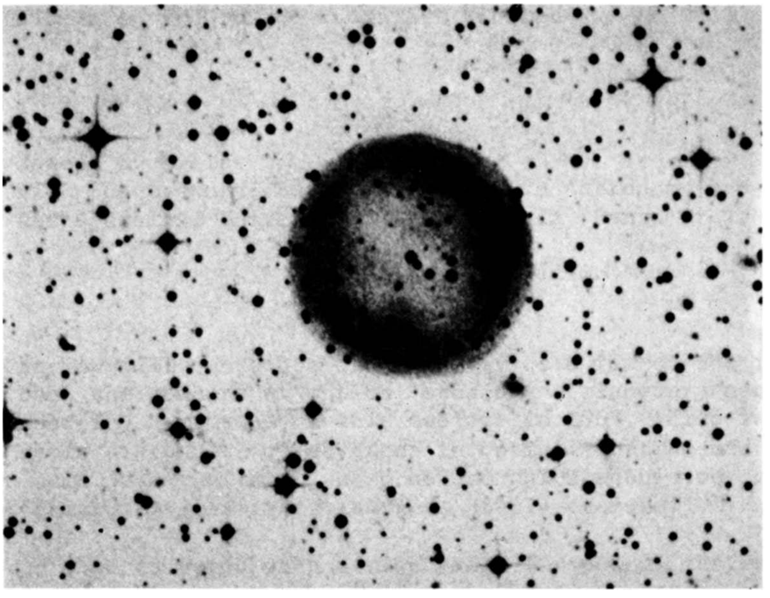

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SESSION II

OBSERVATIONS OF PLANETARY NEBULAE

ADVANCES IN OPTICAL STUDIES OF PLANETARY NEBULAE*

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This review will contain a brief survey of a few of the issues that have been the concern of optical studies of planetary nebulae since the last IAU Symposium on this subject in 1967. Also included will be a short discussion of advances in optical instrumentation and remarks on some selected important problems which should be the concern of future optical investigations of planetaries.

I would like to begin with a discussion of optical instrumentation. While direct pictures on photographic emulsions and photographic spectrograms have historically supplied most of the optical data we have on planetary nebulae, in the last 10 years the photographic emulsion has been increasingly supplanted as the primary photon detector by various devices that depend on the photoelectric effect. The photomultiplier, image-intensifier tube, electronographic camera, and spectrum scanner have made possible enormous increases in the quality of data available. I feel that at present we are in the midst of major new instrumentation advances for optical studies of nebulae that will dramatically affect the subject. At some observatories such as Lick, Kitt Peak, and Hale, the sequential spectrum scanner has been largely replaced by multichannel photoelectric devices capable of simultaneously recording data covering more than 1000 Å of spectrum with resolutions of about 10 Å. This means that not only is it possible to derive accurate intensities for large numbers of spectrum lines in short observing sessions, but it is also possible to make useful observations of much fainter objects than has been possible before; the studies by Ford and his associates of planetary nebulae in external galaxies reported elsewhere in this Symposium are an excellent example of this capability. For direct photographs the image tube and, above all, the electronographic camera have made it possible to obtain two-dimensional data on the morphology and physical structure of nebulae with much greater precision than previously possible. The recent paper by Reay and Worswick (1977) illustrates the application of modern electronographic

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techniques to studies of planetary nebulae. The next major advance, which is taking place now, is the development of area detectors with direct digital readout. At Lick Observatory we are developing a two-dimensional version of our image tube scanner, and elsewhere SEC and SIT television-type detectors are being used. The most exciting prospect for the future is large charge-coupled devices (CCDs) that have much higher quantum efficiencies than photocathodes, especially in the red and near infrared, large dynamic range, high spatial resolution ($\sim 10\ \mu$), and accurate linearity.

If we examine what were the outstanding optical problems associated with planetary nebulae studies 10 years ago, we would certainly include the discrepancy between observations and the predictions of recombination theory. Numerous observations were available which suggested that measured Balmer decrements were not in good agreement with theory in spite of several attempts to make improvements to the theory. This discrepancy was ultimately resolved by the discovery that there were serious errors in the observations, and at present there is little question that the theory of radiative recombination provides an accurate description of Balmer line formation; see Miller (1974) for a more detailed discussion of the history and resolution of this problem.

An associated problem was that of the agreement between theory and observation of the continuum emission from planetary nebulae. Since it is believed that the optical continuum results entirely from atomic processes that are intimately associated with the recombination process, continuum observations provide an additional test of the theory. In this case the optical observations are more difficult because of the relative faintness of the continuum, so that discrepancies could easily be attributed to the observations. In the last six years three photoelectric studies of NGC 7027 have appeared which still leave unanswered questions about the optical continuum. Miller and Mathews (1972) measured the continuum at a number of points between 3400 and 11000 Å. They also measured the Balmer decrement to provide a value for the reddening. With this value they were unable to find a good overall fit of the data to theory for any values of temperature and density, but the best agreement was found for $T_e = 17000°K$. At this temperature the observed points tended to lie above the theoretical curve by increasing amounts toward the red. This red excess could be eliminated by adopting a higher value for the reddening and a lower temperature, but then it must be explained how the Balmer decrement can give a different value for the reddening than the optical continuum. Danziger and Goad (1973) presented continuum observations of NGC 7027 which they found to fit the theory well for a temperature of 18000°K. However, they allowed the reddening to be a free parameter in the fitting procedure, and the best fitting condition was achieved at a higher reddening than that indicated by the Balmer decrement in the Miller and Mathews study; any significantly lower reddening would have resulted in a red excess. Kaler (1976) made interference filter measurements of the NGC 7027 continuum at three wavelengths. The values agree very well with those of Miller and Mathews. Using only his value for the flux at one wavelength in the Balmer continuum, Kaler derived T_e = 11300°K, significantly lower than the above studies. However, for Kaler's adopted nebular parameters, his Figure 1 shows that the set of continuum measurements of the two earlier studies disagrees considerably from the theoretical curve. In fact, his figure shows a better overall fit for the 18000°K curve. We conclude from this discussion that there are still unresolved discrepancies concerning the continuum of NGC 7027 (which, it should be pointed out, is the best observed nebula). How can the continuum appear to be reddened more than the Balmer lines? One possible solution to this problem would be that there is an additional source of continuum emission causing the excess. It is unknown whether dust sufficiently hot to radiate in the red could be present, but this should be considered. Another possibility is the existence of a faint, cool star with m(v) ≈ 14.5 projected on the nebula, though it is likely that such a star would have been noticed if it existed. The second alternative is that there is some problem associated with the reddening determination. Kaler et al. (1976) found evidence for different values of reddening from different lines. Since the same reddening curve was used by Miller and Mathews for the Balmer lines as for the continuum, general slope errors in the curve would affect both the same. For the reddening curve to be the culprit, a local absorption feature, perhaps similar to the diffuse interstellar bands, would have to be located at the wavelength of Hα and cause the emitted Hα to be decreased in intensity about 10-20 percent more than the extinction caused by the general interstellar reddening. A third alternative is that we are seeing the actual exciting star of the nebula, much more highly reddened than the nebular gas itself. This discussion shows that relatively small, but stubborn discrepancies between theory and observation are involved, and we must always be aware that some unexpectedly large source of error has affected the observations. I might add that some lower quality observations of the continuum of NGC 6720 by Hawley and myself also indicate a greater reddening in the continuum than in the Balmer lines. Obviously the continuum of planetary nebulae deserves considerable attention, not only to resolve the discrepancies listed above, but also to provide temperature estimates for the continuum production mechanism.

Cox and Daltabuit (1971) suggested a possible deviation from pure recombination in the form of lower helium triplet lines enhanced by collisional excitation. However, on the basis of theoretical arguments (Brocklehurst 1972) and observations (Peimbert and Torres-Peimbert 1971, Barker 1977) it appears that Cox and Daltabuit considerably overestimated the importance of the effect, and it is likely to be of little consequence for the vast majority of planetary nebulae.

With the availability of new and improved atomic parameters during the past 10 years, temperature and density determinations from the forbidden lines of a variety of ions of elements such as sulfur, argon, and chlorine have become possible. An example of this based on the rich spectrum of NGC 7027 is given by Kaler et al. (1976). It has become clear that density fluctuations and condensations play an important role in the physical structure of planetaries, and simple models of nebulae have been found inadequate to represent the observations. Numerous studies (see, for example, Boeshaar 1974 and Aller and Epps 1976) have shown that the low-ionization species such as S^+ and N^+ are concentrated in condensations of higher density imbedded in a lower density, more uniform background. A particular puzzle has been the strength of [O I] observed in some nebulae. Capriotti et al. (1971) reproduced photographs taken in [O I] emission of NGC 6853 which show that this radiation comes largely from small knots spread out over the nebula. Williams (1973) showed that an explanation of the [O I] emission required shadowed regions behind optically thick condensations, as suggested by Van Blerkom and Arny (1972), and inclusion of charge-exchange interactions in the calculations.

Since the above studies make it clear that planetary nebulae can be structurally very complex, even to the point of having imbedded neutral condensations, the validity of simple ionization correction schemes used for abundance determinations must be carefully examined. Recently, Hawley and Miller (1977) made observations of the Ring Nebula at six positions covering a wide range of ionization level. We found that the correction scheme of Peimbert and his co-workers worked very well for nitrogen and oxygen in the sense that consistent total abundances were obtained over the nebula even though the corrections for unobserved stages of ionization varied by a factor of nearly 30. This is in contrast to the study of Aller and Epps (1975), who found discrepant results for the nitrogen abundance at various places in NGC 7009 using the same approach as we did. However, their less satisfactory results probably came about because they combined line intensities from different studies and instruments, and this object should be re-observed carefully. We found that using only S^+ for the sulfur abundance also gave consistent results over the Ring Nebula, but the derived abundance was about a factor of 10 less than what is considered normal. This likely results from substantial amounts of S^{++} being ignored in the correction scheme used, but suggests that the use of S^+ only may require a roughly constant additional correction factor beyond that provided by the correction formula; this should be investigated further both theoretically and observationally. The big surprise we found in the study of the Ring was the behavior of the [Ne III] lines, as they steadily increased in intensity relative to Hβ as the overall ionization level decreased. In the outer regions where oxygen was predominantly O^+, [Ne III] was very strong and the simple ionization correction formula gave a total neon abundance about 10 times larger than that derived for the other positions and that found in planetaries in general. Proisy (1974) found that direct photographs of the Ring in [Ne III] showed significantly larger images than those recorded in [O III]. Hawley and I have found the same behavior of [Ne III] in NGC 6853, so it isn't peculiar to the Ring. We have no explanation for this behavior of Ne^{++}, but suggest it could arise from peculiarities of the ionization and recombination process.

The above discussion includes only a few of the issues of current interest in optical studies of planetary nebulae. I would like to conclude with a listing of a few of the important problems which should be the concern of future optical investigations; there are of course many others than those mentioned here:

1. The availability of atomic parameters for a wide variety of ions coupled with the speed and accuracy of modern multichannel spectrometers makes it possible to determine densities and temperatures for a wide variety of atomic species. Of particular interest would be temperatures from [O I] and [N I] lines, as these would provide insights into the very low ionization regions about which we have little direct information. Measurements of various lines over a grid of positions covering nebulae would be of considerable value for improving model calculations. Also direct pictures in the light of the brighter emission lines accurately calibrated in flux are now possible by using narrow-band filters and linear detectors, and optical observers would do well to be aware of the possibilities of the VLA and its high spatial resolution for radio-optical studies of planetary nebulae.

2. The continuum deserves concerted attention. We must not overlook the possibility that something fundamental is behind the apparent discrepancy between the reddening from the Balmer lines and the continuum, keeping in mind that observational errors may be the reason. Nevertheless, the continuum provides us with the only direct measurement of the temperature appropriate for the recombination process of hydrogen and, by observations of the relevant discontinuities, doubly-ionized helium when it is present. The observations are difficult and must be done with great care, but are worth it.

3. The problem encountered with strong [Ne III] originating in regions dominated by [O II] in the Ring Nebula and NGC 6853 should be investigated further. It should be established whether this is an effect peculiar to the outer, transition zone or an effect that results from some as yet unexplored aspects of the neon ionization-recombination process.

4. There is little doubt that the infrared radiation of planetary nebulae results from the presence of significant amounts of dust. Efforts should be further pursued to detect this dust by its ability to extinguish optical light. Studies to date have been able only to set upper limits for internal extinction (for example, Osterbrock 1974) or are model-dependent rather than direct detections (for example, Hicks et al. 1976). Perhaps a Fabry-Perot interferometer employed in the approach used by Osterbrock offers the best hope.

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DISCUSSION

Cohen: We have been studying the nebula M1-91 in the optical and infrared. There is evidence for thermal emission by hot dust grains close to the nucleus but not in the general nebula. However, even far from the nucleus we find a nebular continuum that is redder than predicted, although this effect is more marked near the central star. This suggests that dust grains are not likely to be the cause of the extra red continuum emission in nebulae like NGC 7027.

Terzian: From radio Hnα lines $T_e \sim 19000°K$, which agrees with the high temperatures you mentioned, but not with the low value of 11400°K.

Miller: If you take all the optical continuum, the best overall fit is above 15,000°K, but then you have to explain this apparent source of reddening in the continuum.

Panagia: I think that by computing a model with a range of densities (and possibly a range of temperatures, too) as required to explain the forbidden line intensities, the apparent difficulty of fitting the continuous spectrum of NGC 7027 may be removed.

Miller: I was just going to say we also tried mixing 8000°K and 20,000°K and even with that great a range and with any mix, the spectrum always mimics very closely (to within 5%) the continuum for some intermediate temperature.

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Aller: In an independent investigation we found very similar results to those you and Hawley obtained for NGC 6720. All of us found that extrapolation of atomic abundances from ionic concentrations seems to work well for nitrogen in NGC 6720. More recently, we were not so lucky for NGC 7009. It may be that extrapolation procedures work capriciously for different ions in different nebulae under differing circumstances. Observations of additional diagnostic ions are necessary!

Danziger: It seems to me that if the discrepancies between the theory and observation of the continuum are due to a real physical effect in the nebula, it must be fairly sensitive to the physical conditions. For example, the observations of NGC 6302, which is similar to NGC 7027, show very little discrepancy although the observations extended only to 8200 Å. On the other hand, observations of NGC 6210 reveal an excess in the near IR.