ADVANCES IN INFRARED OBSERVATIONS OF PLANETARY NEBULAE

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1. INTRODUCTION

The discovery of infrared continuum emission from NGC 7027 by Gillett, Low, and Stein in 1967 marked the beginning of far infrared observations of planetary nebulae. These early observations verified the predictions (Delmer, Gould, and Ramsey 1967) of infrared fine structure line emission from the SIV ion and also provided a surprise; namely, that the continuum radiation from planetary nebulae was not free-free emission from the gas, but rather that it was thermal emission from heated dust grains. In the ten years which have elapsed since 1967, numerous infrared emission lines have been observed and interpreted in many of the brighter planetary nebulae. In the middle infrared these lines were principally Ne II at 12.8μ, Gillett et al. (1969); SIV at 10.5μ , Holtz, et al. (1971), Gillett, et al. (1972), Aitken and Jones (1973); and AIII at 9.0μ Geballe and Rank (1973) and Gillett and Forrest (1973).

A general review of these earlier observations can be found in Simpson (1975) and therefore I will not give a detailed account of them here. Rather, I will concentrate my discussion of emission lines to a relatively small number of recent observations at both shorter and longer wavelengths which have produced a wealth of new data for line emission. The observations include the emission of permitted lines of atomic hydrogen and helium, forbidden lines of less abundant ions, and the more exotic forbidden transitions of molecular hydrogen. Likewise, the ten years since 1967 have produced a large amount of photometric data on the emission from dust in planetary nebulae. Near infrared emission from planetary nebulae seems to be mostly dominated by free-free emission (Willner, et al. 1972; Persson and Frogel, 1973) while the middle and far infrared emission is dominated in most cases by reradiation from dust,(Gillett, et al. 1973; Cohen and Barlow, 1974). Figure 1. from Cohen and Barlow demonstrated typical energy distribution for several nebulae. Simple models in which dust grains coexist with the ionized gas and are heated by the Lα photon flux of

Yervant Terzian (ed.), Planetary Nebulae, Observations and Theory, 103-110.

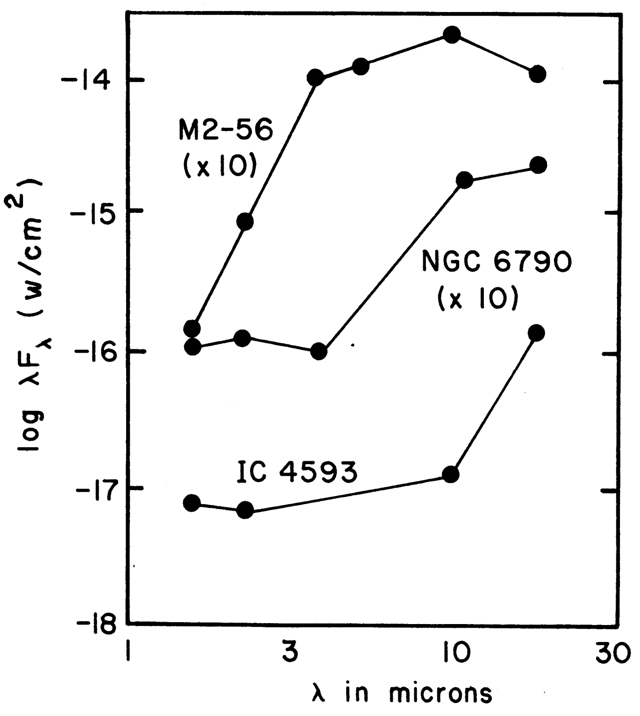

Figure 1. Typical energy distribution for the infrared spectra of planetary nebulae. Cohen and Barlow (1974).

the nebulae are reasonably able to produce the sharp rise in the energy distributions at middle infrared wavelengths. They also generally account for the total luminosities though in some cases these early data indicated that additional sources of ultraviolet radiation might be needed to heat the dust. I refer the reader to Cohen and Barlow and the references therein for a discussion of these earlier results. For the remainder of this paper, I will emphasize more recent observations of the continuum and line radiation from planetary nebulae. Some of these observations have been made with high resolution, others at wavelengths which are not accessible from the ground. Recent spectroscopic measurements have demonstrated that the continuum emission from the dust in many nebulae has a complex shape consisting of numerous emission or absorption features between 3 and 15 microns. At the same time photometric measurements at longer wavelengths seem to indicate that a large fraction of the heavy elements in at least one nebula may be condensed into the grain material. Therefore observations of continuum emission from planetary nebulae may significantly alter the current picture of these objects which is largely based on observations of only the ionized gas.

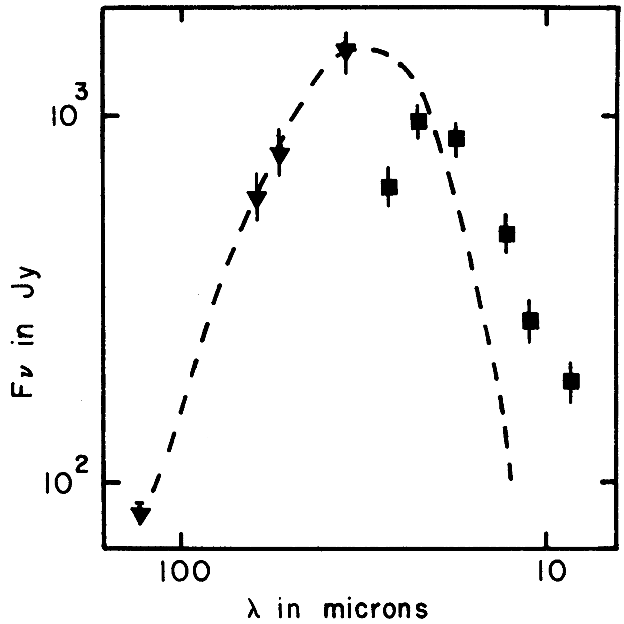

Figure 2. Energy distribution of NGC 7027 in the infrared. The dashed line is a 95°K grey body curve. Telesco and Harper (1977).

2. EMISSION FROM THE DUST OR CONTINUUM

Recent advances in infrared technology have allowed a significant increase in the sensitivity of far infrared photometry. These improvements coupled with the use of high altitude platforms, such as balloons or the NASA Kuiper Airborne Observatory, which are relatively free of telluric absorption, have produced the first bolometric measurements for many astronomical objects. The steeply rising energy distributions of Figure 1. suggest that photometric measurements longward of 20μ are necessary to determine both the color temperature of the dust in nebulae and also for the determination of the total luminosity. Such measurements have recently been carried out by Telesco and Harper (1977). Their data for the planetary nebula NGC 7027 are shown in Figure 2. along with the middle infrared data of Jameson, et al. (1974). From the figure it can be seen that the far infrared data are a rather good fit to the broken line which is a 95°K grey body with an emissivity which is proportional to λ^{-2}. The total luminosity of the nebula inferred from the infrared data and a minimum distance estimate of 500 pc, Cudworth (1974), is at least $2 \times 10^3 L_\odot$. Furthermore, the authors find that the infrared flux from the nebula exceeds the power available for grain heating from trapped Lα by a factor of 3.6. Similar conclusions have been reached by other authors, Becklin, et al.

(1973), on the basis of less extensive data and hence larger uncertainties in the bolometric correction. The new data therefore offers strong support for previous conclusions requiring the distribution of ultraviolet, optical and infrared radiation in the H II region to be strongly moderated by the dust grains. While the far infrared observations have not changed previous models for radiative transfer very much, they have increased the required mass of emitting grain material by about an order of magnitude over previous estimates. Telesco and Harper find that the mass of dust required to fit their observations is about 50% of mass available from heavy elements in the HII region.

From the above discussion it seems likely that grain formation during some early stage of planetary nebula evolution is an efficient process and that planetary nebulae offer an excellent opportunity to study this material. Early observations of the spectra of grain material,(Gillett, et al. 1973) indicated spectral structure typical of a mixture of materials with varying chemical composition. It was found that the strongest emission feature, at 11.3 microns, showed remarkable similarity to the spectra of mineral carbonates. Subsequent higher resolution spectra of this feature,(Bregman and Rank 1975), demonstrated that the 11.3 micron emission was a continuous feature typical of solid material with a nearly exact coincidence in wavelength

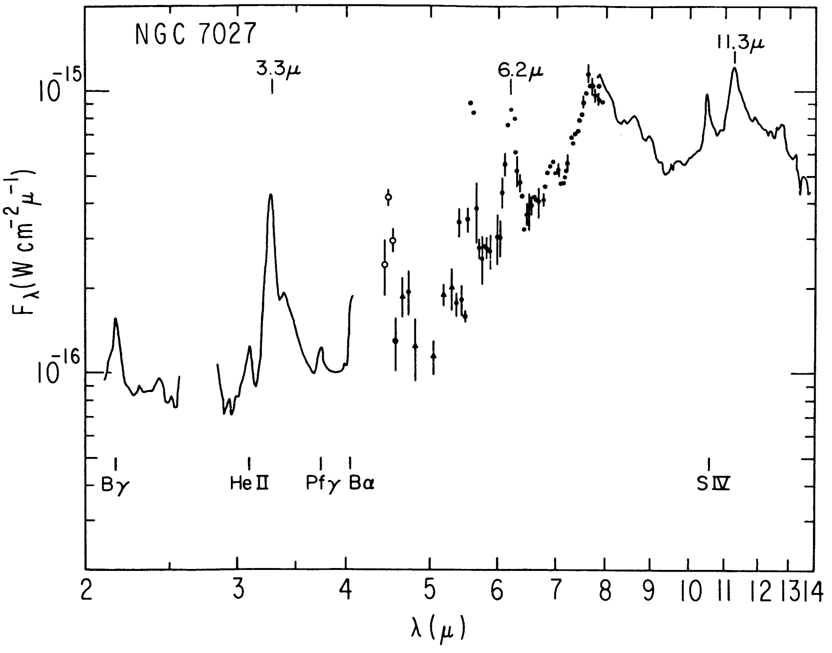

Figure 3. Composite spectrum of the planetary nebula NGC 7027 showing 3.3, 6.2, and 11.3 micron "dust features" and a number of permitted and forbidden lines. Russell, et al. (1977).

https://doi.org/10.1017/S0074180900142640 Published online by Cambridge University Press

and shape to the spectrum of $MgCO_3$. Numerous other features have subsequently been observed in the continuum spectrum of planetary nebulae. Some of the more prominent are at 3.3 and 3.4 microns, Merrill, et al. (1975), and 6.2 microns, Russell et al. (1977). Figure 3. gives an excellent graphical display of the complexity of the dust in NGC 7027. It can be seen from the figure that the continuum emission features produce more infrared flux than either the permitted or forbidden lines. Identification of these features has proved to be a difficult problem. For example, Grasdalen and Joyce (1976), have made a marginally plausible identification of the 3.3 and 3.4 micron feature with the fundamental emission band of the CH^+ molecule while Russell, et al. (1977) consider it more probable that the features are resonances in solid material. Furthermore, the identification of the 11.3 micron feature with $MgCO_3$ material has recently become considerably less certain. Russell, et al. (1977), and Houck (1977) find that additional carbonate resonances near 7 and 30 microns do not appear to be present in the dust spectra with sufficient intensity relative to the 11.3 micron emission for reasonable temperature distributions of the dust. Therefore, it appears that considerably more work, both on laboratory and astronomical spectra will be required to adequately explain the complex infrared continuum emission of planetary nebulae. These efforts should be extremely rewarding scientifically since they hold the promise of a direct measurement of the chemical composition of the grains as well as possible insights into their origin.

3. LINE EMISSION

Extensive infrared fine structure line measurements already exist for a number of planetary nebulae. Until recently, these observations have been limited to wavelengths shortward of 14 microns and to windows of high atmospheric transmission by technical constraints. The observations have proved useful for elemental abundance determinations since new stages of ionization could be detected and the measured ionic abundances do not have a strong dependence on the electron temperature or density of a nebula. Within the last year, two new observations have been made in new and largely unexplored wavelength regions. Russell, et al., (1977) have observed MgIV, MgV, and AVI from NGC 7027 in the 4 to 7 micron region with the Kuiper Airborne Observatory and Greenberg, et al., (1977) have observed SIII at 18 microns in the same nebula. The observations of Greenberg, et al. are particularly interesting since their analysis makes use of the collisional saturation of the upper $^3P_2$ level of the SIII ion to derive a column density directly from the observed surface brightness of the line radiation. Column densities derived under these conditions are extremely insensitive to electron temperature and density; therefore, additional observations of other ions at longer infrared wavelengths where collisional saturation will also be dominant will allow direct and highly accurate comparisons of ionic column densities and hence a more accurate understanding of the ionization structure in planetary nebulae.

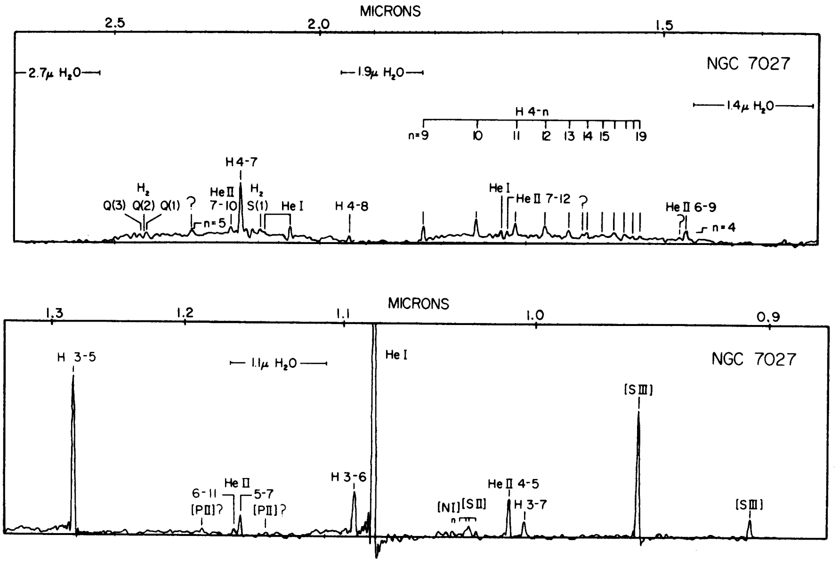

Figure 4. Spectrum of NGC 7027 from 19 to 2.7 microns. Treffers, et al. (1976).

Significant technical and observational advances have also occurred in the very near infrared. The most notable of these has resulted from the dramatic improvement in InSb detectors. Figure 4. is an excellent example of these techniques applied to the observation of planetary nebulae. The data are those of Treffers, et al. (1976), and represent the first observations of molecular hydrogen in a planetary nebula. Three lines of the 1-0 quadrupole spectrum of H_2 appear in the figure near 2.4 microns and offer positive identification of the molecule. The molecules presumably lie in neutral regions near the nebula and could be excited by either collisions or the absorption of ultraviolet photons. Presently, there is insufficient observational data to determine an exact excitation mechanism or how widespread the phenomena may be in other nebulae.

Historically, infrared observations of planetary nebulae were directed toward the study of emission lines from the ionized gas and its associated free-free emission. As so often happens when new areas of research are explored, unexpected and exciting results develop. It has been found that the free-free emission is almost totally masked by an extremely complicated emission spectrum which is largely unexplained but presumably the result of thermal emission by dust. Neutral molecules have been detected in regions surrounding the nebulae or in condensations within the nebulae. Fine structure line measurements have provided new insights into the ionization structure

https://doi.org/10.1017/S0074180900142640 Published online by Cambridge University Press

of the nebulae. Far infrared measurements have provided unexpectedly large masses of grain material associated with the ionized gas. Continued observations will undoubtedly lead to new discoveries and clarify the nature of planetary nebulae, but they also hold out the exciting prospect that the nature of the relationship and interaction between these evolved objects and the interstellar medium may be determined, thus closing a portion of the loop in the continuous cycle of stellar formation and evolution.

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https://doi.org/10.1017/S0074180900142640 Published online by Cambridge University Press

DISCUSSION

Zuckerman: Dr. Rank has mentioned the detection of vibration-rotation lines due to the H_2 molecule in the 2μ spectrum of NGC 7027. I would like to briefly report on some very recent observations of these lines by the Cal Tech infrared group. They find that the spatial extent of the H emission is about 50% larger than the extent of the optical emission suggesting that the H_2 emission originates mainly in a surrounding molecular cloud, possibly the one seen in CO J = 1 → 0 emission. At this point they have not ruled out either the shock or UV excitation models for the H_2, but if the shock model is correct, then the H_2 density is fairly high, $\sim 10^4$ cm^{-3}, just outside the optical nebula. This density is consistent with the density required to excite CO emission. If one assumes a distance for NGC 7027 of ∿2 kpc, then the energy associated with the H shell is quite large and suggests expanding masses of perhaps ∿1 $M_\odot$ for expansion velocities of ∿10 kms^{-1}. A similar mass was derived from the CO observations.

________: Since CIV is seen in the ultraviolet in NGC 7027, there cannot be too much dust inside the nebula. Has anyone tried to model the nebula as surrounded by a shell of dust to fit the infrared and radio observations?

Rank: I don't know if dust has to be inside the nebula. It is model dependent. To the best of my knowledge it seems a reasonable assumption, but I don't think it has been proven.

Panagia: In NGC 7027 a far ultraviolet optical depth for internal dust absorption of 0.3±0.1 is needed to account for the infrared emission (Panagia, Bussoletti, and Blanco (1977) in "CNO Isotopes in Astrophysics, ed. J. Audouze, D. Reidel Publ. Co., Dordrecht-Holland, p. 45). In addition, the emitting dust must be well mixed with the ionized gas. As a consequence, the attenuation of the CIV λ1550 resonance line turns out to be a factor of 3.8±0.8.

Rank: Yes, I agree that there is evidence for the presence of dust within the ionized regions of several planetary nebulae? However, most of the evidence is model dependent, and I tend to agree with Professor Miller's earlier comment that it would be very reassuring to have direct observational evidence for its existence.

Silverglate: Might the 3μ feature be due to ice?

Rank: Russell et al. (1977) have actually suggested water of hydration as a possible explanation for the unidentified 6.2 μ feature, however, they feel that the dust temperature may be too high for hydrated water to be stable. These same arguments would apply to the presence of ice.