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8–13-MICRON SPECTRA OF NGC 7027, BD+30°3639, AND NGC 6572

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ABSTRACT

Observations of the 8–13-μ spectra of the planetary nebulae NGC 7027, BD+30°3639, and NGC 6572 are presented. The spectra consist of both fine-structure line radiation and continuum radiation. The results are discussed in terms of abundances, predicted line strengths, and composition of radiating material.
Subject headings: abundances, nebular — planetary nebulae — spectra, infrared

I. INTRODUCTION

The atomic processes leading to infrared radiation from planetary nebulae have been discussed by Delmer, Gould, and Ramsey (1967, hereafter called DGR), Goldberg (1968), and Flower (1970). The bulk of radiation due to these processes was found to be free-free radiation and line radiation from ions with fine structure in the ground state. Of these lines, the 12.8-μ Ne II line has been observed in IC 418 (Gillett and Stein 1969), and the 10.5-μ S IV line has been observed in a large number of planetary nebulae (Rank *et al.* 1970; Holtz *et al.* 1971; Gillett, Merrill, and Stein 1972, hereafter called GMS). In addition, a large number of planetary nebulae have been found to radiate more continuum energy around 10 μ than expected (Gillett, Low, and Stein 1967; Woolf 1969; GMS). Krishna Swamy and O'Dell (1968) have proposed a model for the excess infrared continuum in which graphite grains in or around the nebula absorb Lyman-α photons and reradiate this energy in the infrared.

NGC 7027, a high-excitation planetary, and BD+30°3639, a very low-excitation planetary, are the two brightest planetary nebulae around 10 μ, and as such they are logical candidates for higher spectral resolution studies of the infrared excess in these objects. NGC 6572, a medium-excitation object, is expected to show strong fine-structure lines, especially the 9.0-μ Ar III line.

In § II the equipment and data reduction are discussed and the observations are presented. In § III the spectra are discussed, first from the point of view of line radiation and then the continuum.

II. OBSERVATIONS

The observations reported here were obtained using the University of Minnesota UCSD 60-inch (152-cm) infrared telescope on Mount Lemmon and the 50-inch (127-cm) telescope at Kitt Peak, during the time interval 1971 June to 1972 June. The spectrometer used was a cooled filter-wheel spectrometer with a resolution of $\Delta\lambda/\lambda \approx 0.015$ in the 8–14-μ range. The observing technique and data reduction are discussed in Gillett and Forrest (1973). The log of observations is given in table 1, including the diameter of the field diaphragm and the total integration time for each night.

The resulting spectra of NGC 7027 and BD+30°3639, corrected to outside the Earth's atmosphere, are shown in figure 1. At each wavelength, the mean and standard deviation of the mean of all measurements at that wavelength are shown. For BD+30°3639 measurements with 11″ and 22″ diaphragms showed no systematic differences, and were averaged together without regard for aperture size. Figure 2 shows the

TABLE 1

LOG OF OBSERVATIONS

Object	Date	Telescope (inches)	Diaphragm Size (″)	Integration Time (s)
NGC 7027..................	1971 Oct. 15	MTL 60	22	3500
	1971 Nov. 7	MTL 60	22	4440
BD+30°3639...............	1971 Oct. 15	MTL 60	11	580
	1972 Apr. 22	MTL 60	22	2780
	1972 May 3	MTL 60	22	900
	1972 June 11	MTL 60	11	6580
	1972 June 17	MTL 60	11	5360
NGC 6572..................	1971 June 14	MTL 60	22	1880
	1972 May 22	KPNO 50	12	1340
	1972 June 17	MTL 60	11	3480

observations of NGC 6572, as well as the earlier broad-band measurements of this object (Gillett and Stein 1970; GMS). A portion of the 1971 June 14 spectrometer observations (the 10.5-μ point) have been reported in GMS but are reproduced here for completeness. As with BD+30°3639, measurements with 11″, 12″, and 22″ beams showed no systematic differences and were averaged together.

Gillett, Low, and Stein (1967) obtained a partial spectrum of NGC 7027 in the 8–14-μ range. With the revised calibration of that data (Woolf and Ney 1969), those

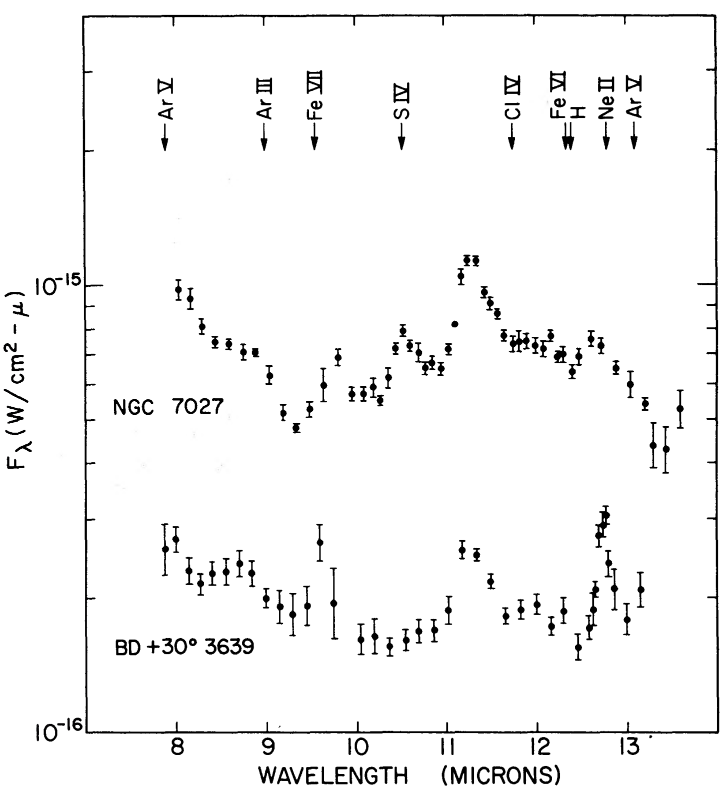

FIG. 1.—The 8–13-μ spectra of NGC 7027 and BD+30°3639. Wavelengths of predicted fine-structure lines are indicated.

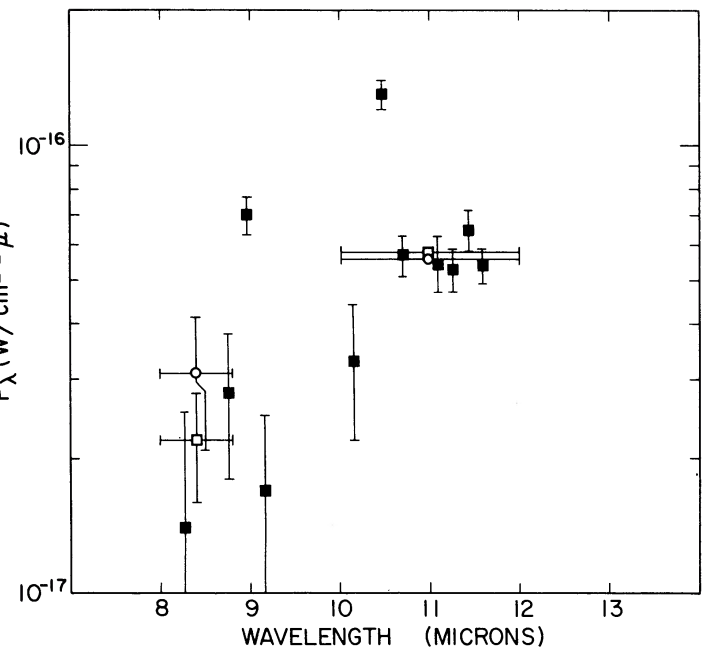

FIG. 2.—The 8–13-μ observations of NGC 6572. *Filled squares*, spectrometer observations reported here; *open circles*, broad-band observations (GMS); *open squares*, broad-band observations (Gillett and Stein 1970); *horizontal bars*, bandpass of broad-band filters.

results are consistent with the measurements reported here. The observations reported here are also in excellent agreement with the broad-band measurements found in Gillett and Stein (1970) and GMS.

III. DISCUSSION

a) *Introduction*

The spectra shown in figures 1 and 2, especially that of NGC 7027, are among the most complex spectra yet observed with this equipment. Evidently, both continuum and discrete line radiation are present in all three spectra. The wavelengths of predicted fine-structure lines are indicated in figure 1. Clearly present are the 10.52-μ S IV line in NGC 7027 and NGC 6572, the 12.78-μ Ne II line in BD+30°3639, and the 9.0-μ Ar III line in NGC 6572, as well as continuum radiation at all wavelengths.

The most striking feature of these spectra is the strong peak around 11.3 μ present in NGC 7027 and BD+30°3639 and not seen in NGC 6572. This feature is broader than the instrumental resolution and so cannot be a single emission line. This feature and the rest of the observed spectra will be discussed in §§ II*b* and II*c*, first the emission-line component and following that, the continuum radiation.

b) *Line Emission*

i) *12.78-μ* Ne II

The strong narrow feature in BD+30°3639 centered at about 12.75 μ is undoubtedly the 12.78-μ Ne II line. Taking the bandwidth of the spectrometer to be 0.16 μ at this wavelength, the integrated flux in this line is about $2.2 \pm 0.3 \times 10^{-17}$ W cm^{-2}. Holtz *et al.* (1971) set a 2 σ upper limit of 1.5×10^{-17} W cm^{-2} for the flux from this line, which would appear to be just compatible with the flux observed here.

The 12.78-μ line has also been detected in IC 418 (Gillett and Stein 1969) with essentially the same integrated flux ($2.1 \pm 0.5 \times 10^{-17}$ W cm^{-2}), and since the Hβ fluxes from IC 418 and BD+30°3639 (after correction for extinction) are very nearly the same (Peimbert and Torres-Peimbert 1971*a*), the relative abundance Ne$^+$/H is nearly the same for both planetaries.

Because BD+30°3639 is a lower-excitation planetary nebulae than IC 418, the near equality of Ne$^+$/H in the two objects would suggest a higher neon abundance in BD+30°3639. A semiquantitative evaluation of this difference can be obtained using the technique used by DGR for estimating the ionization equilibrium of neon. DGR argued from the observed O III/O II ratio and the deduced He$^+$/He^0 ratio, that Ne$^+$/Ne = 0.7 in IC 418. Using the same arguments and consistent data on He$^+$/He^0 and O III/O II (Peimbert and Torres-Peimbert 1971*a*, *b*) for BD+30°3639, it is found that Ne$^+$/Ne < 0.2 for BD+30°3639. Thus, the neon abundance is apparently larger in BD+30°3639 than in IC 418 by at least a factor of 3. The neon abundance in IC 418 is best determined from the observed strength of the 12.8-μ Ne II line since a large fraction of the neon in this planetary is Ne$^+$. Using the formulation of DGR and current estimates of electron temperature, Hβ flux, and reddening (Peimbert and Torres-Peimbert 1971*a*, *b*), the deduced neon abundance for IC 418 is[1] Ne/H = 8×10^{-5}. This value is in good agreement with the average abundance in planetary nebulae (Osterbrock 1970), so it appears that the neon abundance in BD+30°3639 is substantially higher than the average for all planetary nebulae.

ii) *10.52-μ* S IV

The 10.52-μ line has been previously observed in NGC 7027 and NGC 6572 (Holtz *et al.* 1971; GMS), and the results have been discussed in GMS. This line is not seen in BD+30°3639, undoubtedly because of the very low excitation in this object.

iii) *9.0-μ* Ar III

The 9.0-μ Ar III line is clearly seen in the spectrum of NGC 6572. The integrated flux in this feature is $5.2 \pm 1.3 \times 10^{-18}$ W cm^{-2}, where the bandwidth of the spectrometer is taken to be 0.11 μ at 9.0 μ, and the flux from the line is taken to be the difference between the flux measured at 9.0 μ and the average of the fluxes measured at 8.78 and 9.15 μ.

In contrast to S IV and Ne II, Ar III has observable lines in the visual region, so that the strength of the 9.0-μ line, relative to the visual lines of Ar III, is independent of estimates of ionization, and should be easily calculable. DGR have predicted the integrated flux of the 9-μ line in NGC 7027 and NGC 6572 as 7×10^{-17} W cm^{-2}. Since this estimate was made, the collision strengths (for both the visual and infrared lines) have been recalculated (Krueger and Czyzak 1970), and using these later values, the predicted strength of the 9.0-μ line in NGC 6572 is 6.6×10^{-18} W cm^{-2}. Thus, the observed line in NGC 6572 is consistent with this predicted flux.

The revised prediction of the strength of the 9-μ line in NGC 7027 is 8×10^{-18} W cm^{-2}. There could be a feature of about this strength at 9 μ in the spectrum of NGC 7027, but the strong and rapidly changing continuum makes it very difficult to definitely isolate the line at the resolution used here.

iv) *Other Lines*

There is a marginally significant narrow feature at 9.6 μ in BD+30°3639; however, it is in the middle of the ozone band and could possibly be an anomalous measurement. The coincidence of this feature with the Fe VII line at 9.65 μ is undoubtedly

[1] The value deduced here differs from that originally quoted in Gillett and Stein (1969) due to the use of a reduced electron temperature and reddening correction in the present calculation.

fortuitous. Because of the very low excitation in this nebula, essentially no Fe VII would be expected to be present.

The high point at 9.8 μ in NGC 7027 is probably not significant, since it is dominated by a single high measurement.

The strong peak around 11.3 μ in BD+30°3639 and NGC 7027 is the most interesting feature in these spectra. This feature is considerably broader than the instrumental resolution, so if it is a line feature, it must include two or more strong lines. Clearly the test of whether this feature is line emission or continuum is observations with higher spectral resolution. In lieu of this there are two lines of reasoning which suggest that the 11.3-μ peak is a continuum feature: (1) The feature is seen in the strong-continuum, weak-line objects and not seen in the strong-line, weak-continuum object (NGC 6572); and (2) it is seen in a high-excitation planetary NGC 7027, and a very low-excitation planetary BD+30°3639, and not seen in the medium-excitation object NGC 6572, so there appears to be no correlation with excitation of the nebula. These arguments are not conclusive, but for the rest of this discussion will be from the point of view that the 11.3-μ peak is associated with the continuum.

c) Continuum Radiation

Some of the continuum structure, particularly in the spectrum of NGC 7027, is suggestive of absorption features; however, large masses of material would be required if this were the case. For example, the column density of silicate dust required to produce an optical depth of 0.5 in an absorption band around 10 μ is typically 1.5×10^{-4} g cm^{-2} (Hunt, Wisherd, and Bonham 1950). If NGC 7027 were surrounded by a dust shell with this column density, the mass of dust in this shell would be $M_d \approx \pi\phi^2 D^2 s \approx 4 \times 10^{31}$ g, where the angular diameter of the shell ϕ is taken to be 15″ and the distance to NGC 7027, D, is taken to be 1.3 kpc (Cahn and Kaler 1971) and s, the column density of dust in the shell, is assumed to be 1.5×10^{-4} g cm^{-2}. Taking the gas/dust ratio to be 300, the total mass in the shell would be about 6 $M_\odot$ which is much larger than the accepted mass of a planetary nebula (0.2 $M_\odot$). Apparently the spectral features in 8–13-μ range, outside of the isolated line emission discussed earlier, are due to the variation of emissivity with wavelength of the radiating material, and not due to absorption features superimposed on a smooth continuum.

The continuum features in NGC 7027 and BD+30°3639 (particularly the general rise toward 8-μ and the 11.3-μ peak) are not compatible with the emission spectra expected from graphite grains, and have not been seen in the 8–13-μ spectra of late-type stars such as M supergiants, M and C Mira variables, and other long-period variables (Gillett, Low, and Stein 1968; Hackwell 1972; Gaustad *et al.* 1969; Stein *et al.* 1969). Thus, if the dust in planetary nebulae is a remnant of an earlier stage of evolution, then the forerunners of planetary nebulae are not found among the above-mentioned stellar types. On the other hand, if the forerunner of a planetary nebulae is to be found among the above stellar types, then the dust around planetaries is not a remnant of its earlier evolution phase.

The question of the composition of the dust around NGC 7027 and BD+30°3639 can be investigated by comparing the observed spectra of these objects with the laboratory absorption spectra of finely ground minerals. A remarkable similarity of features was found for mineral carbonates, such as $MgCO_3$ whose absorption spectrum, taken from Hunt *et al.* (1950) is shown in figure 3. There is excellent agreement as to position and shape of the 11.3-μ feature and, in addition, these minerals exhibit increasing emissivity toward 8 μ, similar to that seen in NGC 7027 and BD+30°3639. Magnesium carbonate is not the only carbonate with a strong narrow absorption peak near 11.3 μ. Carbonates in general show such a feature somewhere between 11 and 12 μ, and $CaCO_3$ (11.4 μ) and (Ca, Mg)$(CO_3)_2$ (11.3 μ) peak near 11.3 μ.

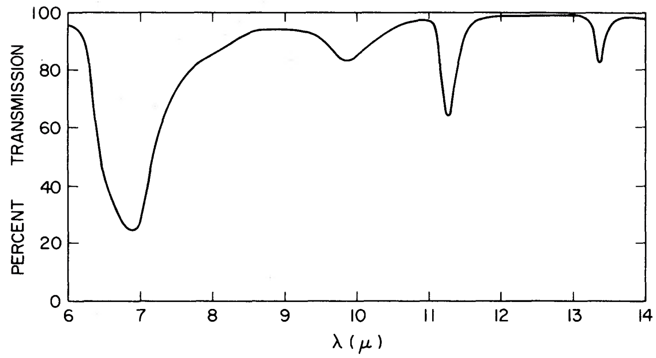

FIG. 3.—The 6–14-μ absorption spectrum of finely ground $MgCO_3$ (Hunt *et al.* 1950). Column density of $MgCO_3$ is 2×10^{-4} g cm^{-2}.

If the 11.3-μ feature is due to carbonate emission, then there must be a second component to the dust in or around NGC 7027 and BD+30°3639. In absorption spectra of carbonates the 11-μ feature is very strong relative to the absorption on either side of this feature (e.g., fig. 3), whereas in the spectrum of NGC 7027 and BD+30°3639 the 11.3-μ feature is not nearly as strong, relative to the continuum on either side of this feature.

There are two obvious observational tests of this possible identification: (1) High-spectral-resolution observations of the 11.3-μ feature. Clearly, if this feature consists of resolvable lines, then the identification with carbonates is nonsense. (2) Medium-resolution observations in the region around 7 μ. If emission from carbonates is present, then the strong carbonate-absorption feature near 6.9 μ should be detectable as an emission feature. Unfortunately, this spectral range cannot be examined from the ground due to H_2O absorption in the Earth's atmosphere, but observations from aircraft or balloons should be possible.

There are also two theoretical points which should be investigated: First, whether or not the observationally required mass of carbonates, e.g., $MgCO_3$ or $CaCO_3$, is consistent with the generally accepted mass of planetary nebulae, and second, the formation and stability of carbonate grains. Discussion of the second point is beyond the scope of this paper; however, understanding of this point will be extremely important if the other tests do not rule out the presence of carbonate minerals.

It is straightforward to estimate the mass of $MgCO_3$ required to account for the 11.3-μ feature: The optical depth of dust in the 11.3-μ feature τ (11.3 μ) is given approximately by

$$\tau(11.3\ \mu) \approx \frac{F_\lambda(11.3\ \mu)}{\mathscr{F}_\lambda(11.3\ \mu, T)} \times \frac{2}{\phi^2}\,,$$

where F_λ (11.3 μ) is the observed excess flux in the 11.3-μ peak, $\mathscr{F}_\lambda$ is the black-body function, T is the temperature of the dust, ϕ is the angular diameter of the radiating shell, and it is assumed that $\tau \ll 1$. The mass of dust (M_d) in this thin shell is given by

$$M_d = \pi\phi^2 D^2 s\,,$$

where s is the column density (g cm^{-2}) of dust in the shell and D is the distance to the radiating region. The column density and optical depth are related by $\tau(11.3\ \mu) = \alpha(11.3\ \mu)s$, where $\alpha(11.3\ \mu)$ is the mass absorption coefficient of the dust in this feature. Putting all this together

$$M_d = \frac{2\pi D^2}{\alpha(11.3\ \mu)} \frac{F_\lambda(11.3\ \mu)}{\mathscr{F}_\lambda(11.3\ \mu, T)}\,.$$

Note that M_d does not depend on the angular size of the radiating shell. Taking the distance to NGC 7027 and BD+30°3639 from Cahn and Kaler (1971), $T = 300°$ K and $\alpha \approx 2 \times 10^3$ cm^2 g^{-1} (from fig. 3), the mass of $MgCO_3$ required to reproduce the 11.3-μ feature is

$$M_d \approx 4 \times 10^{-6} M_\odot \quad \text{(NGC 7027)}, \qquad M_d \approx 1.5 \times 10^{-6} M_\odot \quad \text{(BD+30°3639)} .$$

An upper limit to the amount of $MgCO_3$ in a planetary nebula can be obtained from the total mass of the nebula and the abundance of Mg. In this way it is found that

$$M_{\mathrm{MgCO_3}} < 4 \times 10^{-4} M_\odot .$$

Thus only a small fraction of the available Mg need be in the form of $MgCO_3$ in order to account for the observed 11.3-μ feature in NGC 7027 and BD+30°3639.

IV. SUMMARY OF RESULTS

The results of this investigation can be summarized as follows: (1) The abundance of neon in BD+30°3639 appears to be substantially higher than the average neon abundance in planetary nebulae. (2) The strength of the 9.0-μ Ar III line in NGC 6572, relative to visual lines of the same ion, is in reasonable agreement with expectations, if recent values for the collision strengths of the relevant transitions are used. (3) The shape of the continuum in NGC 7027 and BD+30°3639 is decidedly different from the infrared excess found around cool stars, thus implying substantial differences in the chemical composition of the radiating material. (4) The composition of the radiating material around NGC 6572 is not the same as that around NGC 7027 and BD+30°3639. (5) The laboratory absorption spectrum of some carbonates (such as $MgCO_3$) and the spectra of NGC 7027 and BD+30°3639 show striking similarities, and $MgCO_3$ cannot be ruled out on the basis of the mass required to produce the observed flux from these objects.

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