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8–13 MICRON SPECTROPHOTOMETRY OF PLANETARY NEBULAE

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ABSTRACT

Spectrophotometric observations between 8 and 13 μm are presented for six planetary nebulae: SwSt 1, M1–26, Hb 12, NGC 6790, NGC 6543, and NGC 7027. The first three of these show an emission feature typical of the Trapezium region of Orion and of the circumstellar shells of some oxygen-rich stars. This feature, usually attributed to grains of silicate material, has not been previously observed in planetary nebulae. NGC 6790 shows an emission feature seen in some other planetary nebulae and attributed to silicon carbide grains. Emission lines of Ne II, Ar III, or S IV are seen in five of the nebulae, in qualitative agreement with their excitation class.

The currently available data on planetary nebulae in this wavelength region are reviewed, and it is concluded that there are significant compositional differences in the dust content of these objects. However, they may be divided into two classes according to whether they contain oxygen-rich or carbon-rich grain materials.

Subject headings: infrared: spectra — nebulae: abundances — nebulae: planetary

I. INTRODUCTION

Very few planetary nebulae have so far been studied spectroscopically in the middle-infrared. Of the four spectra in the 8–13 μm region published to date, two (NGC 7027 and BD +30°3639 [Gillett, Forrest, and Merrill 1973, hereafter GFM]) show narrow and so far unidentified features at 8.7 and 11.3 μm while the other two (IC 418 and NGC 6572 [Willner *et al.* 1979]) show a continuum suggestive of the presence of silicon carbide grains. None of these spectra have exhibited the "silicate" or Trapezium-like feature seen so often in a combination of emission and absorption in compact H II regions and which is also characteristic of the circumstellar shells of oxygen-rich supergiants. The spectra show emission lines qualitatively appropriate to the observed optical excitation classes of the objects.

Unlike the emitting dust in H II regions, which is representative of the local interstellar medium, the shells of planetary nebulae consist of ejecta from highly evolved stars, and the study of their composition is relevant to the understanding of the evolution of planetary nebulae. We report here some initial findings of an extended study of planetary nebulae in the middle-infrared.

II. OBSERVATIONS

These results derive from observations using the Anglo-Australian 3.9 m telescope (AAT) in 1977 August and also the Mauna Kea Observatory (MKO) 2.2 m telescope in 1977 June, using the liquid-helium-cooled grating spectrometer developed at UCL. Some additional work has been done with the Cabezon 1.5 m telescope in Tenerife.

The spectrometer employs an array of five arsenic-doped silicon photoconductors, the central three of which sample adjacent spectral elements with a resolution $\Delta\lambda = 0.045$ μm while the outer two have a resolution $\Delta\lambda = 0.15$ μm and are separated in wavelength by 0.85 μm. The spectrometer is operated by a combination of hard-wired logic and a minicomputer, which also performs some real-time data analysis. Spectra are obtained by stepping the grating position through the desired wavelength interval, with the source positioned in alternate beams of a standard dual beam system provided by a focal plane chopper modulated at 12.5 Hz. Wavelength calibration is by reference to known atmospheric absorption features and is accurate to 0.02 μm. Removal of these features is by reference to spectra of standard stars and the use of atmospheric emission spectra taken along the line of sight to the object (Jones 1976). Flux calibration was taken from the spectra of the stars α Tau, α Her, α Cet, and β Gru, and is considered to be accurate to ±20%.

Observations have been made of NGC 6543, NGC 6790, M1–26, SwSt 1, Hb 12, and also of NGC 7027. A log of observations is shown in Table 1, and the individual spectra, after correction for telluric absorption features, are shown in Figure 1. For NGC 7027 the results from the high-resolution detectors alone are shown but $\Delta\lambda$ is increased slightly to 0.055 μm owing to compression of data. In the

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remaining figures the results from the high-resolution scans are shown in the regions of the emission lines from Ar III, S IV, and Ne II at 8.99, 10.52, and 12.81 μm, respectively. The appropriate line intensities are shown in Table 2. In the regions of the spectrum where emission lines were not seen the high-resolution detectors have been convolved to the lower resolution before combining results.

III. INDIVIDUAL SOURCES

In what follows optical data are taken from Kaler (1976) unless otherwise credited. Ionic abundances are derived from the infrared line intensities and either the radio continuum flux when available or hydrogen recombination line intensities, using the methods of Petrosian (1970) and Simpson (1975). The atomic parameters used are as given by Simpson except for the Ne II collision strength, where the more accurate value given by Osterbrock (1974) and Seaton (1975) was used.

a) *M1-26* (*PK 357−0°2*)

This is a very low excitation object ([O III]/H$\beta \approx$ 0.1) and shows a very prominent Ne II emission line at 12.8 μm and a marginal (2 σ) detection of the Ar III line at 8.99 μm. The 8–13 μm continuum of this source (Fig. 1*a*) is similar to the Trapezium emissivity distribution (Forrest, Gillett, and Stein 1975, hereafter FGS).

Spatial scans with the Ne II line centered on one detector indicate a source of FWHM 3″.1 ± 0″.3 in the line and 1″.1 ± 1″.1 in the continuum after allowance for beam size and seeing effects. This suggests that the continuum source is more compact than the ionized region. Observations in 1978 of the Ne II line with a much larger beam (20″, Tenerife) yield substantially the same line intensity after correction of the AAT results for beam size effects, as seen in Table 2. Using the radio data of Milne and Aller (1975) at 5 GHz, we estimate that the ionic fraction Ne II/H (Table 3) is a factor 2.5 greater than the solar value of Ne/H.

b) *SwSt 1* (*PK 1−6°2*)

This object is also of low excitation ([O III]/H$\beta \approx$ 0.3), and its 8–13 μm spectrum is similar to that of M1-26. It shows a prominent Ne II line and an Ar III line at rather more than 3 σ (Table 2). For this object too the 8–13 μm continuum (Fig. 1*b*) is like the Trapezium feature except for an excess in the 8 μm region. A 3.3 μm feature has been observed (B. Jones, private communication).

The diameter of the nebula is not well determined but is less than 10″, and there may well be flux outside our nominal beam diameter of 3″.4. Nevertheless, even without allowing for beam size effects, and assuming $n_e = 10^4$ cm^{-3}, $T_e = 10^4$ K, and a 5 GHz flux of 0.135 ± 0.018 Jy (Milne and Aller 1975), the Ne II/H ratio is overabundant by a factor 2.5 compared with the solar Ne/H value (Table 3).

c) *Hb 12* (*PK 111−2°1*)

Optical data show this to be a medium-excitation object with [O III]/H$\beta \approx$ 5. The 8–13 μm spectrum (Fig. 1*c*) shows a continuum similar to the Trapezium feature. No emission lines are seen to the limits (3 σ) given in Table 2. At short wavelengths neither the 3.3 nor the 3.4 μm feature has been observed (B. Jones, private communication).

There are two significantly different Hβ observations of this object:

$$\text{observed } \log F_{\mathrm{H}\beta} = -10.96 \pm 0.016 \text{ (O'Dell 1963)}$$
$$= -12.00 \pm 0.001 \text{ (Barker 1978)}\,.$$

Beckwith, Persson, and Gatley (1978) have observed

$$F_{\mathrm{B}\gamma} = 31 \pm 4 \times 10^{-20}\ \mathrm{W\ cm^{-2}}\,,$$

which, using recombination theory case B and the ratio of emissivities from Giles (1977) and Osterbrock (1974), implies

$$\log F_{\mathrm{H}\beta} = -9.98 \pm 0.06\,.$$

Barker has calculated the reddening coefficient from

TABLE 1

LOG OF OBSERVATIONS

Object	Dates	Wavelengths (μm)	Beam Diam. (arcsec)	Telescope (m)	Integration Time (s)
Hb 12	1977 Jun 23, 24, 25	8–13	9	2.2 MKO	3500
NGC 6543	1977 Jun 26	10.28–10.76	9	2.2 MKO	800
NGC 7027	1977 Jun 24	8–13	9	2.2 MKO	600
NGC 7027	1978 Apr 24, Dec 8	8–13	20	1.5 Cabezon	3500
NGC 7027	1978 Dec 4	12.63–12.99	9	1.5 Cabezon	300
M1–26	1977 Aug 28	8–13	3.4	3.9 AAT	2000
M1–26	1978 Apr 24	12.63–12.99	20	1.5 Cabezon	500
SwSt 1	1977 Aug 25	8–13	3.4	3.9 AAT	2000
SwSt 1	1977 Aug 25	8.76–9.24	3.4	3.9 AAT	400
SwSt 1	1977 Aug 25	10.28–10.76	3.4	3.9 AAT	200
NGC 6790	1977 Aug 24	8–13	3.4	3.9 AAT	3500
NGC 6790	1977 Aug 24	10.28–10.76	3.4	3.9 AAT	600

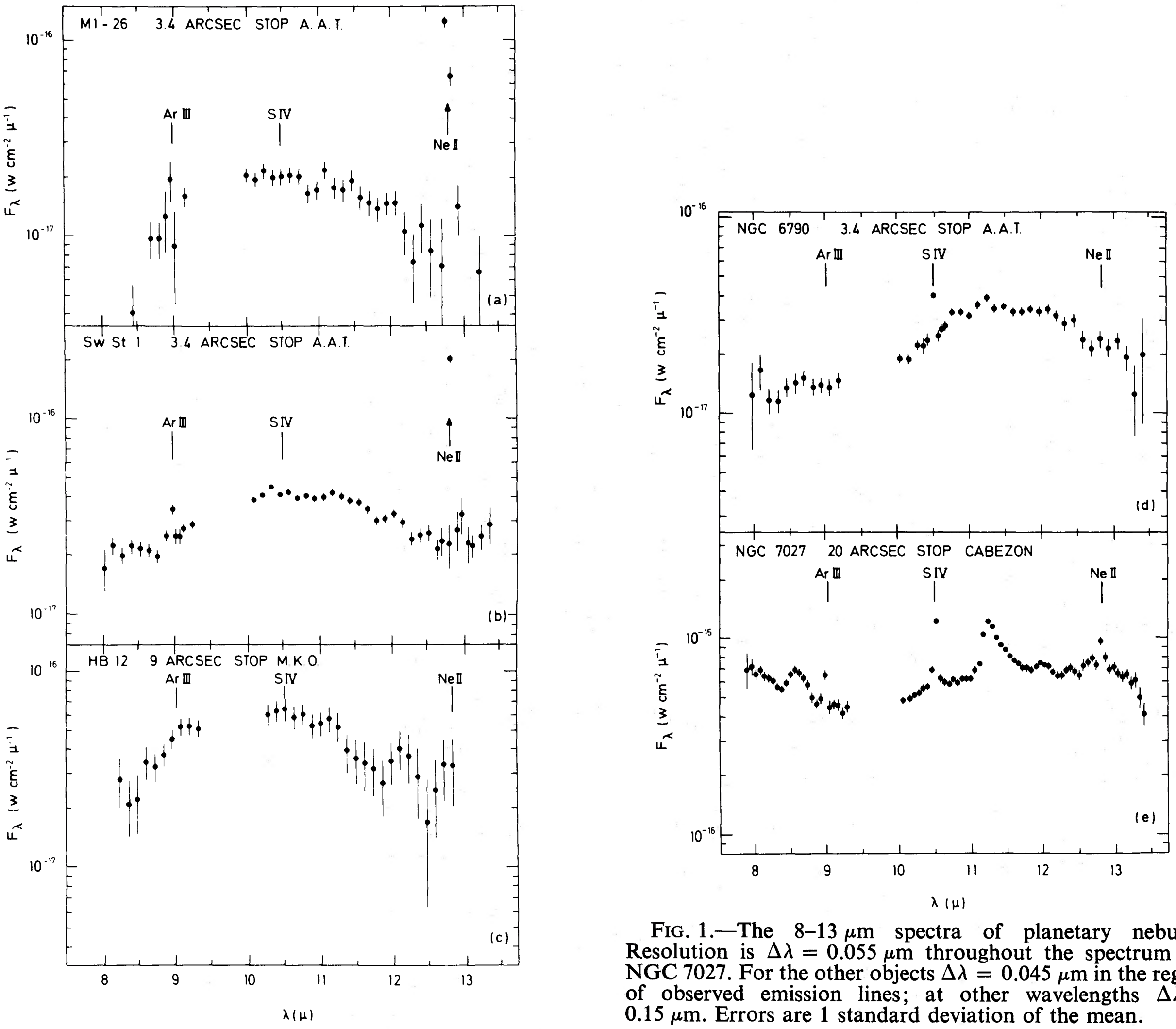

FIG. 1.—The 8–13 μm spectra of planetary nebulae. Resolution is $\Delta\lambda = 0.055$ μm throughout the spectrum for NGC 7027. For the other objects $\Delta\lambda = 0.045$ μm in the region of observed emission lines; at other wavelengths $\Delta\lambda = 0.15$ μm. Errors are 1 standard deviation of the mean.

TABLE 2

LINE INTENSITIES[a]

Object	Beam (arcsec)	8.99 μm Ar III	10.52 μm S IV	12.81 μm Ne II
NGC 6543	9	...	8.5 ± 1.0	...
NGC 6543	Total[b]	...	26.5 (+10.0, −8.5)	...
NGC 6790	3.4	< 0.5	0.98 ± 0.10	0.30 ± 0.25
NGC 7027	9	4.7 ± 1.3	35.8 ± 1.8	9.0 ± 1.5
NGC 7027	20	12.8 ± 2.6	48.8 ± 2.7	19.7 ± 4.0
Hb 12	9	< 2.4	< 1.4	< 1.4
M1–26	3.4	0.4 ± 0.2	< 0.6	7.0 ± 0.4
M1–26	Total[b]	...	...	18.8 ± 3.5
M1–26	20	...	...	17.5 ± 3.0
SwSt 1	3.4	0.44 ± 0.12	0.23 ± 0.15	7.0 ± 0.3

[a] In units of 10^{-18} W cm^{-2}; upper limits are 3 σ.

[b] Derived from spatial scans and assuming circular symmetry.

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TABLE 3

A. PLANETARY NEBULA PARAMETERS

Object	Optical Diam. (arcsec)	Radio Flux (Jy)	N_e[a] (cm^{-3})	T_e[a] (K)	Beam Diam. (arcsec)	Radio Flux in Beam (Jy)
NGC 6543	18	0.77[b]	3.9×10^3	7900	9	0.16[c]
NGC 6790	4.6	0.34[b]	1.2×10^4	12000	3.4	0.12[d]
NGC 7027	12	6.5[b]	4×10^4	11500	9	4.8[e]
Hb 12	2	($H\beta = 1.4 \times 10^{-10}$ ergs cm^{-2} s^{-1})[f]	...	...	...	...
M1–26	4.2	0.32[g]	...	...	3.4	0.13[d]
SwSt 1	< 10	0.14[g]	...	...	3.4	0.14[h]

[a] Values of N_e and T_e are computed from optical line pairs selected from Kaler 1976. Where these were not available, values of $N_e = 10^4$ K and $T_e = 10^4$ K have been assumed.

[b] Radio data from Higgs at 10 GHz.

[c] Radio flux scaled according to Hα contours of Phillips *et al.* 1977.

[d] Assuming circularly symmetric Gaussian profiles for source and beam.

[e] From integration of radio contours (Scott 1973)—see Aitken and Jones 1973*a*.

[f] See text.

[g] Radio data from Milne and Aller at 5 GHz.

[h] Assuming source smaller than beam.

B. IONIC ABUNDANCES AND IONIC FRACTIONS[a]

Object	Region[b]	Ar III/H	Ar III/Ar$_\odot$	S IV/H	S IV/S$_\odot$	Ne II/H	Ne II/Ne$_\odot$
NGC 6543	9″	...	...	1.82×10^{-5}	1.26	...	...
NGC 6543	WN	...	...	1.20×10^{-5}	0.83	...	...
NGC 6790	3″.4	$< 1.9 \times 10^{-6}$	< 0.35	2.92×10^{-6}	0.20	$< 2.3 \times 10^{-5}$	< 0.34
NGC 7027	9″	5.4×10^{-7}	0.08	3.47×10^{-6}	0.24	5.23×10^{-6}	0.08
NGC 7027	WN	10.7×10^{-7}	0.16	3.50×10^{-6}	0.24	9.93×10^{-6}	0.15
Hb 12	9″	$< 2.9 \times 10^{-6}$	< 0.44	$< 1.2 \times 10^{-6}$	< 0.08	$< 1.0 \times 10^{-5}$	< 0.15
M1–26	3″.4	$< 4.2 \times 10^{-6}$	< 0.64	$< 1.7 \times 10^{-6}$	< 0.11	1.72×10^{-4}	2.53
M1–26	WN	...	...	...	...	1.79×10^{-4}	2.63
SwSt 1	3″.4	1.7×10^{-6}	0.26	$< 1.9 \times 10^{-6}$	< 0.13	1.59×10^{-4}	2.34

NOTE.—Using solar values, Ar/H = 6.6×10^{-6}, S/H = 1.45×10^{-5}, Ne/H = 6.8×10^{-5} (Cameron 1973).

[a] Upper limits are 3 σ.

[b] WN = whole nebula.

the Balmer decrement and finds $C = 1.13$; thus de-reddening O'Dell's value gives

$$\log F_{\mathrm{H}\beta} = -9.83 \pm 0.06 ,$$

which agrees well with the estimate from the Beckwith *et al.* observations. Assuming this and, in the absence of other estimates, taking typical values of $n_e = 10^4$ cm^{-3} and $T_e = 10^4$ K, we calculate upper limits for the ionic fractions Ar III/H, S IV/H, and Ne II/H shown in Table 3. Solutions of the equations of ionization balance for a central star in the temperature range 30,000–60,000 K, assuming solar abundances as in Table 3, indicate that at least one of these ratios should exceed the upper limits shown. The line limits are, however, consistent with a density much greater than 10^4 cm^{-3}, when collisional de-excitation will significantly reduce the fine-structure line intensities relative to $F_{\mathrm{H}\beta}$. Such high densities have been suggested by Barker (1978).

d) *NGC 6790* (*PK 37−6°1*)

This source is of high excitation ([O III]/Hβ ≈ 15) and shows the [S IV] emission line at 10.52 μm (Table 2). The 8–13 μm continuum (Fig. 1*d*) is markedly different from that of the other sources presented here but is very similar to that of IC 418 (Willner *et al.* 1979), in which the emission edge near 10.5 μm and the broad maximum in the 11–12 μm range have been attributed to SiC grains. There is also some evidence for a weak 11.3 μm feature and a feature at 8.7 μm; the sharp 3.3 μm feature has also been observed (B. Jones, private communication).

e) *NGC 7027* (*PK 84−3°1*)

This high-excitation object ([O III]/Hβ ≈ 14) has been extensively studied in the infrared (see, for example, the summary by Simpson 1975; and the more recent work of Russell, Soifer, and Merrill 1977 and McCarthy, Forrest, and Houck 1978). The spectrum presented here (Fig. 1*e*) was obtained with a beam diameter of 20″ centered on the infrared peak and is similar to previously published work, showing strong features at 11.3 and 8.7 μm. The continuum has been shown to rise to a strong peak at 7.7 μm, just outside the atmospheric window, by high-altitude aircraft observations (Russell, Soifer, and Willner 1977). Emission lines in beam diameters of 9″ and 20″ from Ar III, Ne II, and S IV are seen with intensities tabulated in Table 2 and ionic abundances in Table 3.

f) NGC 6543 (PK 96+29°1)

Optical data show this to be a medium–high-excitation nebula with [O III]/H$\beta \approx 6$. The emission line [S IV] is observed (Table 2). Spatial scans in [S IV] give a full width at half-height of 15″.9 ± 2″.8 with our 9″ diameter beam, indicating a source diameter of 13″.2 + 3″.4 after deconvolution; this compares with the radio (George, Kaftan-Kassim, and Hartsuijker 1974), and the Hβ and [O III] (Phillips, Reay, and Worswick 1977) size of 16″–17″.

Observations were made only within 0.25 μm of the emission line, and a complete spectrum was not obtained for this object. At 10.5 μm the observed continuum flux in the 9″ diameter beam was $1.7 \pm 0.3 \times 10^{-17}$ W cm^{-2} μm^{-1}.

IV. 8–13 MICRON CONTINUUM

At present there appear to be continuum spectra in the 8–13 μm region available for eight planetary nebulae. These are NGC 7027 (GFM; Bregman and Rank 1975; Aitken and Jones 1973*b*; Russell, Soifer, and Willner 1977; this work), BD +30°3639 (GFM), IC 418, NGC 6572 (Willner *et al.* 1979), M1–26, SwSt 1, NGC 6790, and Hb 12 (this work). Of these spectra, three (M1–26, SwSt 1, and Hb 12) show an emission feature similar to that seen in the Trapezium NA (Ney-Allen) infrared source (FGS), and two show strongly the unidentified features at 11.3 and 8.7 μm (NGC 7027 and BD +30°3639). Of the remaining three, two show a feature identified as silicon carbide (IC 418 and NGC 6790) also seen in the spectra of some carbon stars (Treffers and Cohen 1974; FGS; Merrill and Stein 1976*a*), and one (NGC 6572) has a similar spectrum but showing less contrast in the silicon carbide feature. In addition, NGC 6790 has weak features at 11.3 and 8.7 μm superposed on its otherwise IC 418–like spectrum.

It is evident that this small sample exhibits a wide variety of continuum features, and this is interpreted as indicating substantial compositional differences among planetary nebulae. This is in contrast to the situation occurring in compact H II regions, where the majority of sources are well fitted by a single emissivity curve represented by the spectrum of the Trapezium source (and usually attributed to silicates), seen in a combination of emission and absorption (Aitken and Jones 1973*a*, 1974; Gillett *et al.* 1975; Willner 1977).

The spectra display four characteristics which occur in varying proportions in the nebulae. These are (1) the "silicate" or Trapezium feature; (2) the "SiC" or carbon star excess feature; (3) a smooth continuum; and (4) the 11.3 and 8.7 μm features (although the identification of these features is uncertain, present evidence suggests that they appear together, and in the following we shall assume this).

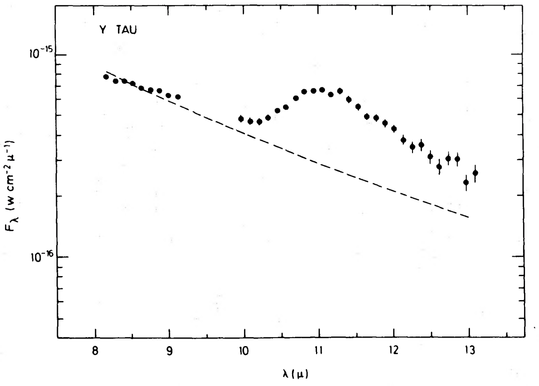

FIG. 2*a*

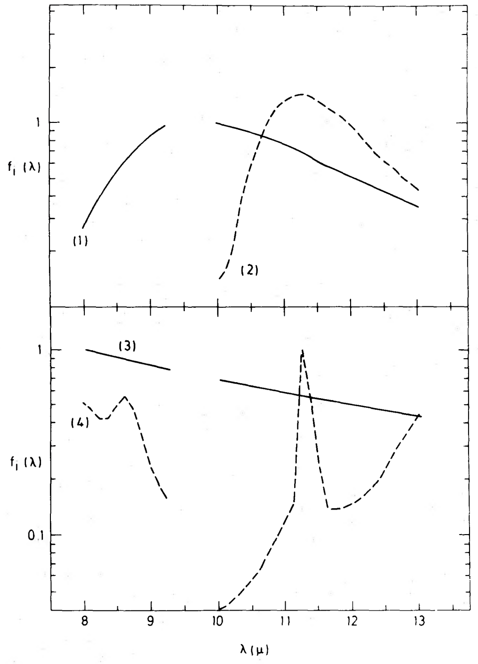

FIG. 2*b*

FIG. 2.—(*a*) The 8–13 μm spectrum of the carbon star Y Tau; the dashed line represents a 2000 K Planck function. (*b*) The emissivity functions $f_{1-4}(\lambda)$ discussed in the text: $f_1(\lambda)$ is taken from the Trapezium source in Orion (an oxygen-rich H II region), $f_2(\lambda)$ is derived from the infrared excess of Y Tau (a carbon star), and $f_4(\lambda)$ is from the ionization front in the Orion Nebula; $f_3(\lambda)$ is a smooth function of form $\lambda^{-1.8}$.

We have attempted to synthesize the spectra of the eight planetary nebulae in terms of these components by assuming that each spectrum is a linear combination of the contributions 1–4, weighted separately by four Planck functions.

Significant mismatches occur between the observed astronomical features and laboratory spectra of their presumed terrestrial counterparts. In the case of silicates, Day and Donn (1978) have shown that the astronomical features are similar to amorphous condensates of silicate materials. However, to avoid difficulties of this sort, we have used where possible observational data to derive the wavelength dependence of the contributions in the following way:

1. The Trapezium NA source spectrum divided by a 250 K Planck function (FGS) is taken as representing $f_1(\lambda)$; this is shown in Figure 2*b*.

2. The infrared excess seen in some carbon stars (Merrill and Stein 1976*b*) frequently shows a marked increase in emission near 10.5 μm, the longitudinal optical phonon frequency in silicon carbide. This enhanced emission is maintained to a less well defined decrease at about 12.7 μm, corresponding to the transverse phonon frequency. The broad feature thus defined appears together with varying proportions of a smooth background in excess of the radiation from the underlying star. To reduce contamination by this smooth background, we have considered an object in which there appears to be little excess above the underlying star for wavelengths less than 10 μm. Observations of the carbon star Y Tau (Fig. 1*a*) using the Cabezon 1.5 m telescope show a spectrum with a particularly strong feature and in which the 8–10 μm region closely fits a 2000 K Planck function defined by the photometry of Gillett, Merrill, and Stein (1971). We have taken the excess above this blackbody curve to represent the contribution $f_2(\lambda)B(\lambda, T'_2)$, where T'_2 is the unknown temperature of the dust shell around Y Tau. This excess has a significant contribution at 13 μm whereas the "average excess" of FGS does not, although they are similar in other respects. FGS appear to have fitted Planck functions through points less than 10 μm and greater than 12.5 μm in the 8–13 μm spectra of a number of carbon stars, and have averaged the resultant excesses; this process forces the feature to be close to zero outside the range 10–12.5 μm. We have avoided the possibility of introducing a systematic error in this way, but it may be that the 13 μm excess contains a contribution due to the smooth background discussed below as component (3).

The curve $f_2(\lambda)$ is shown in Figure 2*b* for T'_2 taken as 800 K.

3. A simple power-law dependence $f_3(\lambda) = 1/\lambda^n$ is taken as a smooth background. To be specific, we have put $n = -1.8$, considered to be appropriate for graphite (Leung 1975), which appears to be necessary in carbon stars (Bregman and Bregman 1978) and at least one protoplanetary object (Russell, Soifer, and Willner 1978).

4. The most extreme form of this type of spectrum known is that of the ionization-front region of Orion (Gillett, private communication; Aitken *et al.* 1979*b*). The 11.3 μm feature appears here with much greater contrast than in other sources, being about 10 times stronger than the neighboring background; the spectrum also has a fairly high contrast 8.7 μm feature. The continuum rises at short and at long wavelengths and superficially resembles silicates seen in absorption. However, the rise toward 8 μm is almost certainly associated with a 7.7 μm peak, which is seen for instance in NGC 7027, HD 44179, and M82, and which does not occur with silicates in absorption (Forrest *et al.* 1978). It seems likely that the 11.3, 8.7, and 7.7 μm features are all related (e.g., Russell, Soifer, and Willner 1978), and the association of the slope of the 8–9 μm region with silicate absorption is in doubt. The continuum at longer wavelengths may be due to a contribution not representative of the other features. However, it is assumed that there is a contribution $f_4(\lambda)$ as indicated by the Orion bar spectrum divided by a Planck function of unknown temperature, T'_4. Figure 2 shows $f_4(\lambda)$ for the case of $T'_4 = 200$ K.

For convenience, each of the emissivity functions $f_{1-4}(\lambda)$ is normalized to unity at some part of the spectrum, as shown in Figure 2. It is assumed that each planetary spectrum is made up of optically thin contributions of the emissivity functions; the linear combination

$$F_\lambda = \sum_{i=1}^{4} a_i f_i(\lambda) B(\lambda, T_i)/B(10\ \mu\text{m}, T_i)$$

is formed for each nebula, and a search is made through parameter space to minimize the quantity

$$\chi^2 = \sum_\lambda (F_{\lambda\,\text{obs}} - F_\lambda)^2/\epsilon_\lambda^2\ ,$$

where ϵ_λ is the error associated with the observed flux $F_{\lambda\,\text{obs}}$, yielding values for a_{1-4}, T_{1-4} for each component. (The data points to which emission lines contribute significantly are of course excluded from this procedure.) We have included the factor $B(10\ \mu\text{m}, T_i)$, which normalizes $B(\lambda, T)$ to unity at 10 μm, for computational reasons. Because of this, a_i measures the amounts of each contribution $f_i(\lambda)$ nearly independently of T_i. The physical amounts of each component can in principle be found from the product $a_i B(10\ \mu\text{m}, T_i)$, the mass absorption coefficient of the material and the size of the source. However, such an estimate depends strongly on the adopted grain temperatures, and in the present case T_2 and T'_2, T_4 and T'_4 cannot be independently determined. This is because the relevant terms in F_λ involve the ratio of two Planck functions of temperatures T and T'. The wavelength dependence of this ratio may change only slightly over a wide range of coupled values of T; an extreme example is for all values of $T = T'$, when the ratio is always unity. We have therefore obtained fits in which T'_2 and T'_4 are arbitrarily fixed with $T'_2 = 270$ and 800 K, and $T'_4 = 200$ K. These substitutions do not affect the form of the best-fit function, the amplitudes a_2 and a_4, or the goodness of fit, but they do change the grain temperatures T_2 and T_4. In Table 4 we present the best-fit values of the fractional amplitudes

$$a'_i = a_i \Big/ \sum_{j=1}^{4} a_j$$

and the temperatures T_i together with the goodness of fit parameter χ^2/N_f. The interpretation of the latter is not straightforward because ϵ_λ does not contain errors inherent in the fitting functions f_1, f_2, and f_4,

TABLE 4

8–13 MICRON CONTINUUM FIT PARAMETERS

			TRAPEZIUM		C-STAR EXCESS		GRAPHITE		ORION BAR	
OBJECT	N_f	χ^2/N_f	a'	T	a'	T	a'	T	a'	T
C-rich Planetary Nebulae										
i) T(Y Tau) = 270 K:										
NGC 6790	37	1.8	0	...	0.31	142	0.69	188	0	...
NGC 7027	63	2.8	0	...	0.08	151	0.45	168	0.47	228
IC 418	25	1.9	0	...	0.26	120	0.74	200	0	...
NGC 6572	13	0.6	0	...	0.24	231**	0.76	155	0	...
BD + 30°3639	26	1.6	0	...	0	...	0.68	218	0.32	179
ii) T(Y Tau) = 800 K:										
NGC 6790	37	1.8	0	...	0.31	205	0.69	188	0	...
NGC 7027	63	2.8	0	...	0.08	224	0.45	168	0.47	228
IC 418	25	1.9	0	...	0.26	166	0.74	200	0	...
NGC 6572	13	0.6	0	...	0.24	491**	0.76	155	0	...
BD + 30°3639	26	1.6	0	...	0	...	0.68	218	0.32	179
O-rich Planetary Nebulae										
Hb 12	32	0.4	1	250	0	...	0	...	0	...
M1–26	30	0.7	1	201	0	...	0	...	0	...
SwSt 1	42	5.0	1	197	0	...	0	...	0	...
SwSt 1	38	1.9	0.70	180	0.10	500*	0.20	500*	0	...
SwSt 1	40	7.4	0	...	0.33	1000*	0.67	208	0	...
SwSt 1†	34	1.5	1	187	0	...	0	...	0	...

NOTE.—* ±50%; ** ±100%; otherwise ±10% or better.

† Fit to 8.7–13 μm.

and high values of χ^2/N_f will result, especially where the fitted spectrum is of higher quality than those from which these functions have been derived. This is particularly true in the case of NGC 7027; consideration of the errors involved in determining f_4, the dominant nonanalytic contribution, reduces χ^2/N_f to about unity from its tabulated value of 2.8. In other cases the fits should be regarded as acceptable for $\chi^2/N_f \lesssim 2$. The best-fit solutions to each of the planetaries are shown in Figure 3. All the spectra are consistent with an interpretation in terms of varying proportions of these ingredients, none of which have been derived from the spectra of planetary nebulae.

Analysis shows that the contribution from nonsilicates in Hb 12 and M1–26 does not reduce the value of χ^2/N_f, and satisfactory fits are not obtainable without the silicate contribution. The fits presented (Figs. 3*a* and 3*b*) contain only the function $f_1(\lambda)$, and only two free parameters are required to give a very good fit to the data. Although silicates alone give a good fit to SwSt 1 for wavelengths longer than 8.7 μm, for the whole spectrum good fits are obtained only with the inclusion of contributions from $f_2(\lambda)$ and $f_3(\lambda)$ (Figs. 3*c* and 3*d*). Owing to the high temperatures required for these contributions, the amplitudes correspond to very small amounts of components (2) and (3). As with Hb 12 and M1–26, satisfactory fits are unobtainable without the silicate contribution.

In a similar way it is found that silicates are unnecessary in the remaining five sources (Figs. 3*e*–3*i*), and all are constrained to contain no silicates. Further, χ^2/N_f is not reduced by the inclusion of $f_4(\lambda)$ in either NGC 6790, IC 418, or NGC 6572, nor is the contribution $f_2(\lambda)$ required in BD +30°3639. The requirement of the contribution $f_2(\lambda)$ indicates the presence of carbon-rich grain materials in NGC 6790, IC 418, NGC 6572, and probably NGC 7027. Although $f_2(\lambda)$ is not required in BD +30°3639, the presence of $f_3(\lambda)$ in this and the members of the carbon-rich group makes it probable that this too contains carbon-rich grain materials.

The nature of the 11.3 and 8.7 μm features is still speculative. Allamandola and Norman (1978) have suggested that these, together with the features observed at 3.3, 3.4, and 7.7 μm, may be due to fluorescence excited by UV irradiation; this mechanism was first suggested by Gillett (Russel, Soifer, and Willner 1977). Although these features are seen in a variety of sources, the identification and classification of the objects are secure only in the case of planetary nebulae, some WC stars (Aitken *et al.* 1979*a*), and an ionization-front region in Orion. With the exception of the last source, an oxygen-rich H II region (Peimbert and Torres-Peimbert 1977), the remainder of these objects appear to be carbon rich.

It is clear that the eight planetary nebulae fall into two categories depending on the presence of oxygen-rich or carbon-rich grain materials. In the category of C-rich planetaries, we would place NGC 7027, BD +30°3639, NGC 6790, NGC 6572, and IC 418. Planetary nebulae are usually considered to be C rich, and C/O substantially greater than unity has

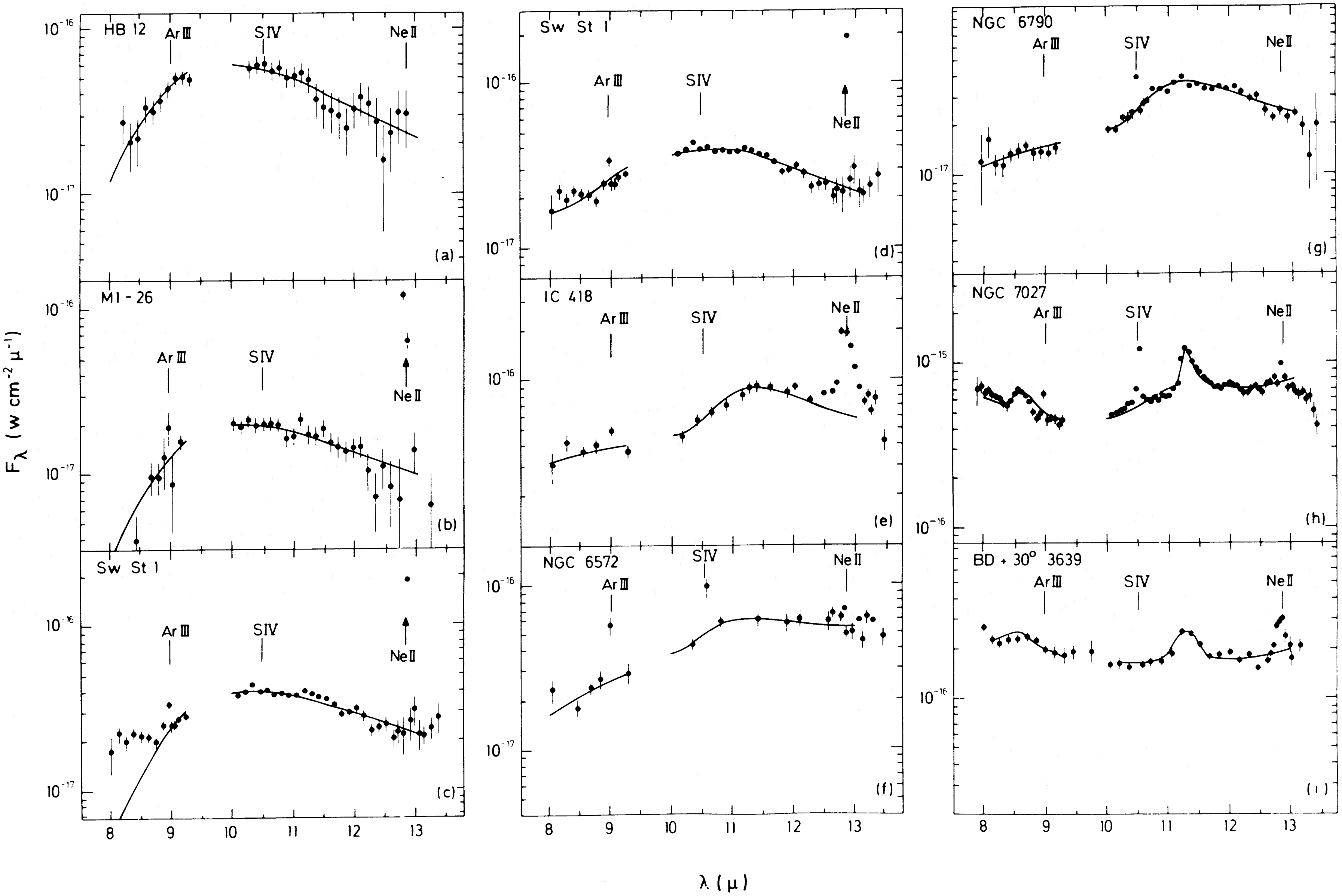

FIG. 3.—Best-fit solutions to the observed continuum spectra of linear combinations of contributions 1–4 (see text). Fig. 3*i* is from GFM and Figs. 3*e* and 3*f* from Willner *et al.* (1979). In Fig. 3*c* SwSt 1 is fit with contribution 1 only, and in Fig. 3*d* with 1, 2, and 3.

been established for about 10 objects (Shields 1978*a*; Aller 1978). Of these, only NGC 7027 belongs to the present sample and has C/O $\approx$ 3 (Shields 1978*b*). There appear to be no reliable optical data indicating C/O < 1 in any planetary nebula. However, on the basis of their 8–13 μm spectra we would place Hb 12, M1–26, and SwSt 1 in an O-rich category, although SwSt 1 seems also to require a small amount of an additional, warmer component, which could be graphite.

The questions arise whether these two classes correlate with other observable properties and whether they represent separate evolutionary tracks, are different stages in a single evolutionary sequence, or are due to an original misclassification of the objects. Let us consider the last possibility, that some of the objects may not be bona fide planetary nebulae. There is little question regarding the planetary nebula status of NGC 7027, BD +30°3639, NGC 6790, NGC 6572, and IC 418, although the first two have rather extreme properties. When we turn to the oxygen-rich objects, we find that M1–26 has been classified by Sanduleak and Stephenson (1972) as a "very low excitation compact nebula"; they question whether such objects are conventional planetary nebulae. Studies of planetary nebulae in the Magellanic Clouds (Sanduleak and Philip 1977) reveal a class of similarly low excitation objects which have luminosity more appropriate to Population I objects. There appears, therefore, to be some doubt about the classification of M1–26 as a planetary nebula. Recent radio observations of Hb 12 (S. Kowk 1978, private communication) indicate that the electron density falls off as $1/r^2$, not typical of shell structure but perhaps indicating a very young or pre–planetary nebula; here too there may be a misclassification. SwSt 1 has a WC 9 central star typical of many planetary nebulae, and there is no reason to question its classification. Here we have an oxygen-rich envelope and a presumably carbon-rich central star. We may conjecture that the envelope represents the remnants of an earlier precursor phase and that the warmer, "graphite" component is associated with the central star.

It is clear that with only one undoubted planetary nebula in the oxygen-rich category the questions raised at the beginning of the previous paragraph cannot yet be answered. However, if we were to extend the selection criteria to what are sometimes considered to be pre–planetary nebulae, we would include, among others, Hb 12 and also HM Sge and V1016 Cyg, which have been recently observed to have strong silicate emission (Puetter *et al.* 1978; Aitken, Roche, and Spenser 1979). This suggests that oxygen richness is a characteristic of some young or pre–planetary nebulae, deriving from the atmosphere of the precursor star, and that oxygen richness may be a transitory phase in the development of these objects as planetary nebulae.

V. LINE RADIATION

Although a full discussion of ionic fractions and elemental abundances in these planetary nebulae requires a proper consideration of ionization structure, which is not possible without knowledge of the luminosity and spectrum of the central stars, it is in order to consider some rough and qualitative conclusions which may be drawn.

Using available radio data and the procedures outlined at the beginning of § III, we have estimated ionic fractions averaged over the extent of the sources included in our beam size. These are shown in Table 3. Fuller treatment, including models of ionization structure where possible, will be presented in a later publication.

In the low-excitation nebulae M1–26 and SwSt 1, the Ne II line at 12.81 μm is prominent. Using radio data from Higgs (1971) and Milne and Aller (1975), we find that the ratio Ne II/H for these objects exceeds the ratio Ne/H for the solar system by a factor 2.5 so that these objects are overabundant in neon by at least this factor. A similar overabundance of neon has been reported by Aller (1978) and Peimbert and Torres-Peimbert (1977).

In contrast, the high-excitation planetaries NGC 6790 and NGC 7027 have small ionic fractions of Ne II, S IV, and Ar III, assuming solar abundances for these elements. The small fractions of Ne II and Ar III are understandable, considering the excitation class of these objects, but S IV/S is also low. The case of NGC 7027 has been discussed by Aitken and Jones (1973*b*), where it is shown that the large density variations of up to 2×10^5 cm^{-3} in this object (Hummer and Seaton 1973) and a value of S IV/S $\approx$ 0.5 expected from a consideration of the optical spectrum (Seaton 1968) lead to an approximately solar value of the sulfur abundance.

VI. CONCLUSIONS

Observations of the 8–13 μm spectra of the planetary nebulae M1–26, SwSt 1, Hb 12, and NGC 6790 show that the first three of these exhibit features similar to those seen in the Trapezium region of Orion, in many compact H II regions, and in the circumstellar shells of late-type oxygen-rich giants. These are the first planetary nebulae to show such features, which are usually attributed to the presence of silicate grains and are associated with formation in an oxygen-rich environment. NGC 6790 shows a spectrum similar to the excess emission from carbon stars and attributed to SiC grains.

The eight planetary nebulae for which 8–13 μm spectra presently exist can be divided into two classes on the basis of their observed emissivity features: those containing oxygen-rich grain materials and those containing carbon-rich materials and sometimes exhibiting the unidentified features at 11.3 and 8.7 μm. Although there is some doubt about the classification of two of the oxygen-rich objects, there appears to be no reason to question the planetary nebula status of SwSt 1.

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REFERENCES

Aitken, D. K., Barlow, M., Roche, P. F., and Spenser, P. M. 1979*a*, in preparation.
Aitken, D. K., and Jones, B. 1973*a*, *M.N.R.A.S.*, **165**, 363.
———. 1973*b*, *Ap. J.*, **184**, 127.
———. 1974, *M.N.R.A.S.*, **167**, 11P.
Aitken, D. K., Jones, B., Roche, P. F., and Spenser, P. M. 1979*b*, *Astr. Ap.*, in press.
Aitken, D. K., Roche, P. F., and Spenser, P. M. 1979, in preparation.
Allamandola, L. J., and Norman, C. A. 1978, *Astr. Ap.*, **63**, L23.
Aller, L. H. 1978, in *IAU Symposium No. 76, Planetary Nebulae*, ed. Y. Terzian (Dordrecht: Reidel), p. 225.
Barker, T. 1978, *Ap. J.*, **219**, 914.
Beckwith, S., Persson, S. E., and Gatley, I. 1978, *Ap. J.* (*Letters*), **219**, L33.
Bregman, J. D., and Bregman, J. N. 1978, *Ap. J.* (*Letters*), **222**, L41.
Bregman, J. D., and Rank, D. M. 1975, *Ap. J.* (*Letters*), **195**, L125.
Cameron, A. G. W. 1973, *Space Sci. Rev.*, **15**, 121.
Day, K. L., and Donn, B. 1978, *Ap. J.* (*Letters*), **222**, L45.
Forrest, W. J., *et al.* 1978, *Ap. J.*, **219**, 114.
Forrest, W. J., Gillett, F. C., and Stein, W. A. 1975, *Ap. J.*, **195**, 423 (FGS).
George, D., Kaftan-Kassim, M. A., and Hartsuijker, A. P. 1974, *Astr. Ap.*, **35**, 219.
Giles, K. 1977, *M.N.R.A.S.*, **180**, 57P.
Gillett, F. C., Forrest, W. J., and Merrill, K. M. 1973, *Ap. J.*, **183**, 87 (GFM).
Gillett, F. C., Forrest, W. J., Merrill, K. M., Capps, R. W., and Soifer, B. T. 1975, *Ap. J.*, **200**, 609.
Gillett, F. C., Merrill, K. M., and Stein, W. A. 1971, *Ap. J.*, **164**, 83.
Higgs, L. A. 1971, *Pub. Ap. Branch, NRC, Canada*, Vol. **1**, No. 1.
Hummer, D. G., and Seaton, M. J. 1973, *Mém. Soc. Roy. Sci. Liège*, 6th Ser., **5**, 225.
Jones, B. 1976, Ph.D. thesis, University of London.
Kaler, J. B. 1976, *Ap. J. Suppl.* **31**, 517.
Leung, C. M. 1975, *Ap. J.*, **199**, 340.
McCarthy, J. F., Forrest, W. J., and Houck, J. R. 1978, *Ap. J.*, **224**, 109.
Merrill, K. M., and Stein, W. A. 1976*a*, *Pub. A.S.P.*, **88**, 285.
———. 1976*b*, *Pub. A.S.P.*, **88**, 294.
Milne, D. K., and Aller, L. H. 1975, *Astr. Ap.*, **38**, 183.
O'Dell, C. R. 1963, *Ap. J.*, **138**, 1018.
Osterbrock, D. E. 1974, *Astrophysics of Gaseous Nebulae* (San Francisco: Freeman).
Peimbert, M., and Torres-Peimbert, S. 1977, *M.N.R.A.S.*, **179**, 217.
Petrosian, V. 1970, *Ap. J.*, **159**, 833.
Phillips, J. P., Reay, N. K., and Worswick, S. P. 1977, *Astr. Ap.*, **61**, 695.
Puetter, R. C., Russell, R. W., Soifer, B. T., and Willner, S. P. 1978, *Ap. J.* (*Letters*), **223**, L93.
Russell, R. W., Soifer, B. T., and Merrill, K. M. 1977, *Ap. J.*, **213**, 66.
Russell, R. W., Soifer, B. T., and Willner, S. P. 1977, *Ap. J.* (*Letters*), **217**, L149.
———. 1978, *Ap. J.*, **220**, 568.
Sanduleak, B., and Philip, A. G. D. 1977, *Pub. A.S.P.*, **89**, 792.
Sanduleak, N., and Stephenson, C. B. 1972, *Ap. J.*, **178**, 183.
Scott, P. F. 1973, *M.N.R.A.S.*, **161**, 35.
Seaton, M. J. 1968, *M.N.R.A.S.*, **139**, 120.
———. 1975, *M.N.R.A.S.*, **170**, 475.
Shields, G. 1978*a*, *Ap. J.*, **219**, 559.
———. 1978*b*, *Ap. J.*, **219**, 565.
Simpson, J. P. 1975, *Astr. Ap.*, **39**, 43.
Treffers, R., and Cohen, M. 1974, *Ap. J.*, **188**, 545.
Willner, S. P. 1977, *Ap. J.*, **214**, 706.
Willner, S. P., Jones, B., Puetter, R. C., Russell, R. W., and Soifer, B. T. 1979, in preparation.

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