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INFRARED SPECTRA OF IC 418 AND NGC 6572

S. P. WILLNER,[1] B. JONES,[2] R. C. PUETTER,[1] R. W. RUSSELL,[1] AND B. T. SOIFER[1,3]
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ABSTRACT

Spectrophotometric observations from 2 to 4 and 8 to 13 μm of NGC 6572 and from 4 to 13 μm of IC 418 are reported. Also reported are observations of the size of IC 418 in the optical and at 1.65 and 2.2 μm. Both planetary nebulae emit more radiation than expected from recombination at wavelengths longer than ~4 μm; this radiation is attributed to heated dust. The spectra show a plateau from 10.5 to 13 μm, and this peak is tentatively attributed to emission from large silicon carbide particles. Fine-structure emission lines are also discussed; the presence of [Ar III] but not [Ne II] in NGC 6572 suggests that ions having the same ionization potential can nevertheless have different fractional abundances.

Subject headings: infrared: spectra — nebulae: planetary

I. INTRODUCTION

Infrared emission from planetary nebulae is usually attributed to a combination of recombination[4] and radiation from heated dust. At wavelengths near 10 μm, the dust emission often greatly exceeds the recombination contribution, often by two orders of magnitude (for a summary of observations, see Cohen and Barlow 1974). The dust emission decreases toward shorter wavelengths, and near 2 μm recombination alone can account for the observed emission for most planetaries (Khromov and Moroz 1972; Willner, Becklin, and Visvanathan 1972; Persson and Frogel 1973*b*). A few nebulae, including IC 418, are brighter than expected from recombination even at wavelengths as short as 1.6 μm; the excess radiation has been attributed to thermal radiation from very hot dust grains.

Infrared spectra are available for only a few planetary nebulae (Gillett, Forrest, and Merrill 1973; Merrill, Soifer, and Russell 1975; Treffers *et al.* 1976; Russell, Soifer, and Merrill 1977, hereafter RSM; Russell, Soifer, and Willner 1977, hereafter RSW; Russell *et al.* 1977; Aitken *et al.* 1979; Grasdalen 1979), although individual spectral lines and features have been measured in several more (see, e.g., Gillett, Merrill, and Stein 1972). The two best-studied planetaries, NGC 7027 and BD +30°3639, show emission features at 3.3/3.4 μm, 6.2 μm, 7.7 μm, 8.6 μm, and 11.3 μm. These features, or at least some of them, are common to a variety of other objects (Russell, Soifer, and Willner 1978 and references therein) and have been attributed to emissivity peaks in the dust that produces most of the infrared radiation. The 3.3 μm peak is especially intriguing, because it seems to appear with at least two different shapes (RSM). In most objects, including NGC 7027 and BD +30°3639, the 3.3 μm feature includes a wing at longer wavelengths, but in IC 418 the longer wavelength wing is not present.

The present observations of IC 418 were intended to test whether the other emission features are associated with the 3.3 μm feature alone or only with the 3.3 μm feature that includes a 3.4 μm wing. In fact, weak features at 6.2 and 7.7 μm appear to be present. The 8.6 and 11.3 μm features were not detected and are much weaker relative to the 3.3 μm feature than in other objects. Instead, a broad feature, tentatively attributed to solid silicon carbide particles, was seen near 11 μm.

NGC 6572 is a planetary nebula that is relatively bright in the radio, but, unlike IC 418, NGC 6572 emits only recombination radiation near 2 μm. Both 2–4 μm and 8–13 μm spectra were obtained, and a peak near 11 μm similar to that in IC 418 was seen. The observations and a description of the spectra are presented in § II, while § III discusses the results for the dust features, for the atomic emission lines, and for measurements of the angular size of IC 418. An attempt is made to relate IC 418 and NGC 6572 to the carbon-rich evolutionary sequence suggested by Zuckerman *et al.* (1976, 1978).

II. OBSERVATIONS

a) *Spectroscopy*

Observations were made with the Mount Lemmon 1.5 m telescope in 1976 December and 1977 January, March, May, and October. The focal plane diaphragm was 17″ in diameter, and the spectral resolving power ($\lambda/\Delta\lambda$) was approximately 65. Airborne observations of IC 418 were made in 1978 February and of NGC 6572 in 1977 July from the Kuiper Airborne Observatory. The instrument has been described by RSW, and the present observations were made with a focal plane diaphragm 28″ in diameter. The results, converted to

[1] University of California, San Diego.

[2] School of Physics and Astronomy, University of Minnesota.

[3] California Institute of Technology.

[4] As used here, recombination includes free-bound, free-free, bound-bound, and two-photon processes.

flux density outside the Earth's atmosphere through observations of standard stars (Puetter *et al.* 1979), are shown in Figure 1. Data on IC 418 between 2 and 4 μm were taken from RSM. No effort was made to correct for the different beam sizes; the 4–8 μm observations of IC 418 should probably be lowered by between 20 and 40% to be compared with the ground-based observations. The data points for NGC 6572 shown as open circles represent averages of data at three wavelengths; the spectral resolution of these points is thus only 0.06 μm. The observations presented here have better signal-to-noise ratio and wavelength coverage but are in good agreement with those obtained earlier by Gillett, Forrest, and Merrill (1973), Gillett and Stein (1969), and Geballe and Rank (1973).

From 2 to 4 μm, the spectrum of NGC 6572 is in agreement with that predicted from recombination theory and radio observations (Higgs 1971 and references therein) to within the statistical uncertainties of the observations. The Brackett γ and α and Pfund δ recombination lines are prominent. No evidence for a broad feature at 3.3 μm is seen, although the data of Table 1 permit a weak feature to be present. The absence of Pfγ is not explained, but the noise in that part of the spectrum is relatively high.

At 8 μm, the flux density of NGC 6572 is well above the predicted level from recombination and appears to increase to longer and possibly to shorter wavelengths. There is some indication that the 7.7 μm emission feature found in other objects might be present, but further observations are needed to confirm this. There is no evidence of a peak at 11.3 μm. Fine-structure lines of [Ar III] and [S IV] are present (Gillett, Merrill, and Stein 1972; Gillett, Forrest, and Merrill 1973), but the [Ne II] line at 12.8 μm was not detected. Fluxes of various lines and other features are given in Table 1. The shape of the spectrum between 8 and 13 μm is similar to that of IC 418 and is discussed below. The data presented here are in agreement with those of Grasdalen (1979) if allowance is made for his smaller beam size (11″).

IC 418 is about a factor of 2 brighter between

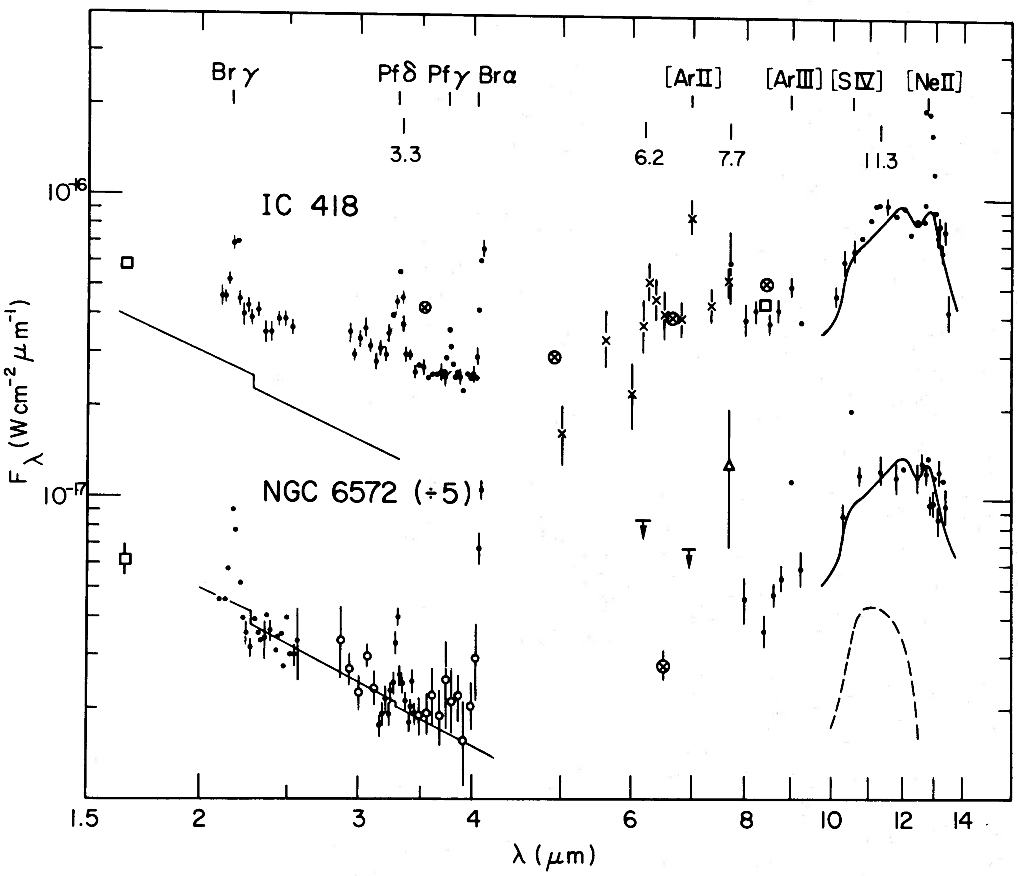

FIG. 1.—The 2–14 μm spectra of IC 418 and NGC 6572. Error bars are shown when the statistical uncertainty exceeds 5%. The 2–4 μm data on IC 418 are from RSM. The open circles represent averages of adjacent data points giving a resolution of 0.06 μm. The squares represent broad-band observations with the 17″ beam used for all of the ground-based observations. The circled x's represent broad-band observations obtained from the KAO with the 28″ beam used for all the airborne observations. No corrections for beam size have been applied to the observations. Wavelengths of various emission lines and features are marked. The solid lines from 2 to 4 μm show the recombination flux density predicted from radio observations. The solid lines near 11 μm show the emissivity of large silicon carbide particles plus a constant emissivity of 40% of the peak value. The dashed line shows the shape of the silicon carbide emission seen in IRC +10216 (Forrest 1974) plus a constant emission equal to 22% of the peak.

TABLE 1

FLUXES IN SPECTRAL FEATURES

λ (μ)		NGC 6572 (10^{-14} W m^{-2})	IC 418 (10^{-14} W m^{-2})
2.17.....	Bγ	1.15 ± 0.15	1.22 ± 0.18
3.27.....	Unidentified + Pfδ	0.47 ± 0.10	1.8 ± 0.2
3.30[a]....	Pfδ	0.35	0.44
3.74.....	Pfγ	< 0.7	0.62 ± 0.11
4.05.....	Bα	3.7 ± 0.2	2.8 ± 0.2
7.00.....	[Ar II]	< 3.8	4.9 ± 0.6
8.99.....	[Ar III]	5.7 ± 0.7	2.0 ± 0.9
10.52.....	[S IV]	10.6 ± 1.3	< 2.4
12.81.....	[Ne II]	< 2.9	28 ± 2

[a] Fluxes predicted from radio observations.

TABLE 2

FLUX DENSITY FROM IC 418 AS A FUNCTION OF BEAM SIZE

DIAPHRAGM DIAMETER (arcsec)	TELESCOPE[a]	FLUX DENSITY (10^{-12} W m^{-2} μm^{-1}) 1.65 μm	2.2 μm	LINE FLUX (arbitrary units) Hα + [N II]
5.0......	C	...	0.07	
8.0......	B	0.26	0.18	0.30
9.7......	C	...	0.23	
11.......	B	...	...	0.58
15.......	B	0.53	0.45	0.84
17.......	D	0.59	0.47	
18.......	A	...	0.46	
20.......	C	...	0.52	
22.......	B	0.68	0.58	0.97
24.......	B	...	0.59	0.98
31.......	B	0.77	0.67	0.98
36.......	A	...	0.66	
44.......	B	0.79	0.72	1.00
56.......	A	...	0.70	
101.......	A	...	0.75	
Total predicted from radio flux density...........		0.48	0.34	

[a] Key to telescope: A = Mt. Wilson 60 cm; B = Mt. Wilson 1.5 m; C = Mt. Wilson 2.5 m (Willner *et al.* 1972 corrected to present flux density calibration); D = Mt. Lemmon 1.5 m (λ_{eff} = 2.3 μm corrected to 2.2 μm).

2 and 4 μm than predicted from radio observations (Higgs 1971 and references therein). The existence of an excess was known from previous measurements of the equivalent width of Bγ (Hilgeman 1969) and from broad-band observations (Willner, Becklin, and Visvanathan 1972); the latter also show an excess at 1.65 μm. The flux density of the excess is a slowly increasing function of wavelength. Bγ and α and Pfγ recombination lines are present with reduced equivalent width, confirming the continuum excess. The 3.3 μm feature is broader than the Pfδ line seen in NGC 6572 but lacks the 3.4 μm wing (RSM) seen, for example, in NGC 7027. The continuum rises slowly from 8 to 13 μm and is at a level much above that expected from recombination. Superposed on this rise is a broad peak between 10.5 and 12.5 μm, similar in shape to an emission feature seen in late-type carbon stars; the carbon star emission feature is attributed to silicon carbide (Forrest 1974). Weak 6.2 and 7.7 μm features appear to be present. The [Ne II] and [Ar II] fine-structure lines are strong. The [Ne II] line has the same equivalent width as measured by Gillett and Stein (1969); [Ar III] and [S IV] are weak or absent. IC 418 is the second planetary nebula, after BD +30°3639 (Russell *et al.* 1977), in which [Ar II] has been detected.

b) *Size of IC 418*

Broad-band photometric observations of IC 418 were made with a series of circular focal plane diaphragms in order to compare the spatial extent of the 2–4 μm excess emission to the extent of the emission from ionized gas. Such observations are useful because the nebula is highly symmetric. Previous observations (Willner, Becklin, and Visvanathan 1972) showed that the 2.2 μm excess was not confined to the region of the central star. The present observations extend to larger diaphragm sizes, include some color information, and include direct measurements of the Hα size.

Infrared observations were obtained in 1972 February, October, and December with the 1.5 m and 60 cm telescopes at Mount Wilson. The results are given in Table 2, together with the Hα + [N II] observations obtained in 1973 January with the Mount Wilson 1.5 m telescope. These were obtained with the same optical arrangement as the infrared observations, except that the chopper was turned off; a photomultiplier with an S-20 photocathode and an interference filter that isolated the Hα and [N II] λ6583 emission lines were used. The optical observations were uncalibrated and have been arbitrarily normalized. The size of the Hα emission appears to be the same as expected on the basis of high-resolution radio observations (Terzian, Balick, and Bignell 1974). Table 2 also gives the total recombination flux density as predicted (Willner, Becklin, and Visvanathan 1972) from radio observations that include the entire nebula (Higgs 1971).

Figure 2 shows the measurements of Table 2 normalized to the measurement through the largest diaphragm. The data indicate that the infrared emission is coming from a region at least as large as the optical emission. Furthermore, the infrared surface brightness is relatively larger near the outside of the nebula than is the Hα + [N II] surface brightness. The excess radiation is not enhanced near the central star; it is even possible that up to half the 2.2 μm excess comes from outside the ionized region. The 1.65–2.2 μm color becomes bluer closer to the central star.

III. DISCUSSION

a) *Feature at 3.3 μm*

The feature at 3.3 μm has been attributed to a peak in the emissivity of dust (RSM); molecular bands, as suggested by Grasdalen and Joyce (1976), for example, are also possible. In IC 418, the Pfδ line contributes about $\frac{1}{4}$ of the flux observed for the 3.3 μm feature,

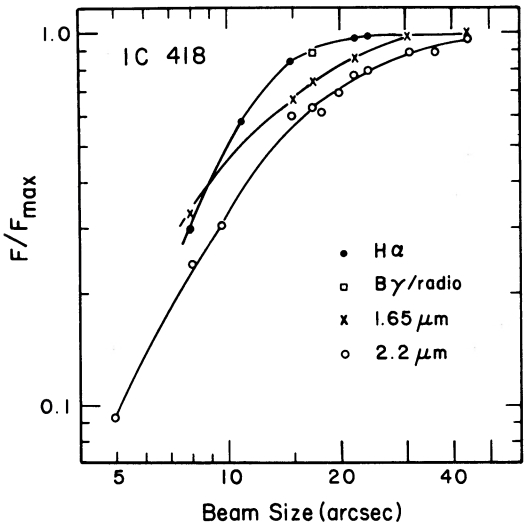

FIG. 2.—Flux from IC 418 as a function of beam size. The measurements at each wavelength are normalized to the measurement with the largest beam size. The square represents the ratio of the Bγ flux measured with a 17″ beam to the Bγ flux predicted from radio observations of the whole nebula (Higgs 1971). The points labeled Hα represent the sum of Hα and [N II] λ6583 with the latter actually contributing about $\frac{2}{3}$ of the measured flux. G. Righini-Cohen and M. Simon (private communication) have measured Bα and Bγ with an 11″ beam; their measurements fall below the curve in the figure, near $F/F_{max} = 0.45$.

while the relative line contribution is much smaller for other objects in which a broad 3.3 μm feature has been observed.

In other sources that show a 3.3 μm feature, a 3.4 μm wing and features at 6.2, 7.7, and 11.3 μm have always been seen. Compared with NGC 7027, the 6.2 and 7.7 μm features in the spectrum of IC 418 are a factor of 2 or more weaker relative to the 3.3 μm feature. It is difficult to assess the strength of an 11.3 μm feature in IC 418 because of the uncertainty in the continuum shape. The local maximum observed at 11.3 μm is much broader than the 11.3 μm features seen in NGC 7027 and other objects and could be entirely due to silicon carbide, as discussed below. On the other hand, if a lower continuum level is adopted, an 11.3 μm feature as strong as that in NGC 7027 could be present. We emphasize that the apparent weakness of the various emission features in IC 418 is not due to their being veiled by a strong continuum, for the continuum is redder in NGC 7027 than in IC 418. It thus appears that different relative feature strengths may be associated with different shapes of the 3.3 μm feature, and in particular the lack of a 3.4 μm wing may be associated with weak 6.2, 7.7, and possibly 11.3 μm features.

The two shapes observed for the 3.3 μm feature do not appear to be correlated with the excitation of the object. A molecular band might vary in shape as a function of temperature; unfortunately the present data are not sufficient to indicate a correlation of shape with temperature. Allamandola and Norman (1978) have suggested that the 3.3 μm band may be due to methane adsorbed on dust grains. If this identification is correct, the 3.4 and 7.7 μm bands ought always to accompany the 3.3 μm feature (Allamandola, Greenberg, and Norman 1979). The weakness of these features in IC 418 thus appears to cast doubt on an identification of the 3.3 μm feature as methane in this object.

b) Other Dust Features

One of the most striking features in the spectra of these two planetaries is the rise in flux density between 9 and 11 μm. Both planetaries show the rise and a plateau from 11 to 13 μm. The spectrum of IC 418 appears to decline at longer wavelengths; such a decline may also be present in NGC 6572. The shape of the feature is suggestive of that of silicon carbide, which has been observed in emission in many late-type carbon stars (Forrest 1974) but never before in a nebula. The emissivity, as measured in our laboratory (Russell and Stephens 1979), of silicon carbide particles about 5 μm in diameter is shown in Figure 1 for comparison. Figure 3 shows the 8–13 μm data alone, so that the shape and strength of the 11–13 μm feature can be judged without any prejudice from the laboratory measurements. Particles larger than about 0.5 μm (Treffers 1973) have a different emissivity than is typical for the small particles seen around carbon stars (Forrest 1974) in that there is a second emissivity peak near 13 μm. The presence of this peak, and thus of relatively large particles, is probably required if silicon carbide is to fit the observed data. If such large

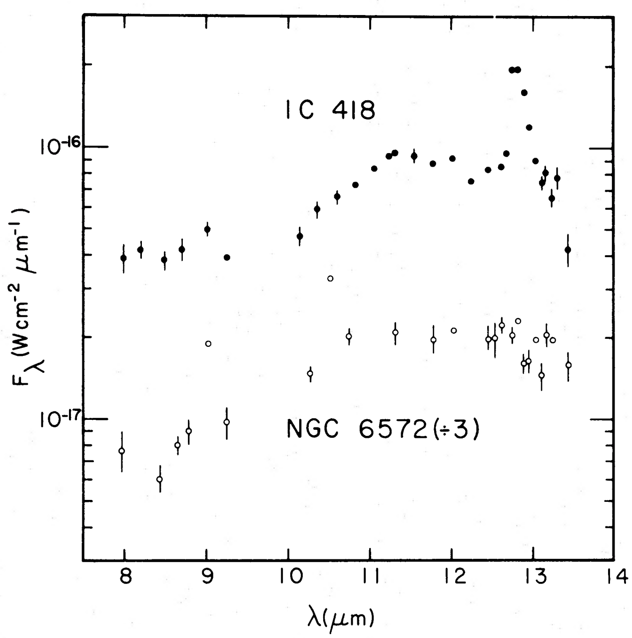

FIG. 3.—The 8–14 μm spectra of IC 418 and NGC 6572. The same data as in Fig. 1 are shown without any lines representing laboratory measurements so that the reader can form a better idea of the shape of the feature suggested to be silicon carbide.

particles are really present, their origin in these planetary nebulae and their absence in carbon star dust shells must be explained. The shape of the plateau between 11 and 12 μm depends on the shape mixture of particles (Treffers and Cohen 1974), and a distribution having more prolate particles would have higher emissivity near 11 μm than near 13 μm and thus better fit the observed spectra. However, better spectra of these faint objects are required before the silicon carbide identification can be considered definite.

If the identification of silicon carbide is correct, the dust particles evidently condensed in an environment having more carbon than oxygen, and planetary nebulae such as IC 418 and NGC 6572 might be the end point of the evolutionary sequence that includes carbon stars (Zuckerman *et al.* 1976, 1978). Additional evidence that planetary nebulae may be carbon-rich comes from recent ultraviolet observations (Bohlin, Marionni, and Stecher 1975; Bohlin, Harrington, and Stecher 1978). Although derivation of carbon abundances is model dependent, Bohlin, Harrington, and Stecher (1978) and Shields (1978) conclude that carbon is more abundant than oxygen in a number of nebulae. Unfortunately, IC 418 and NGC 6572 were not studied, but if the former nebula is indeed carbon-rich, it lends support to the identification of the 3.3 μm feature as a resonance of a CH bond, either in a molecule in the gas phase (Grasdalen and Joyce 1976; Black 1978) or in a solid particle (Knacke 1977; Allamandola and Norman 1978; Allamandola, Greenberg, and Norman 1979).

c) Excess Continuum in IC 418

The excess continuum radiation from 2 to 4 μm from IC 418 has been attributed to thermal emission from very hot dust grains (Willner, Becklin, and Visvanathan 1972). The color temperature of the excess can be estimated from the data in Table 2, if the expected recombination flux density is subtracted. Figure 2 shows that about half the Hα flux originates inside a 10″ beam. The grain temperatures are 1350 K for a 10″ beam and 950 K for a 44″ beam, if the grain emissivity $\epsilon \propto \lambda^{-2}$, or hotter if a less steep emissivity law applies. The decrease in temperature suggests that most of the grain heating is due to direct radiation from the central star, as is the case for most planetary nebulae (Ferch and Salpeter 1975).

The temperature of a grain is determined by the balance between incident and emitted radiation. For temperatures in the range of interest, the grains may be considered as being in thermal equilibrium; nonequilibrium processes, which may be important in the interstellar medium, are significant only at low grain temperatures (Purcell 1976). For IC 418, the grain temperature

$$T_g = 61(U/I)^{1/4}(r/1'')^{-1/2}(T_*/3 \times 10^4 \text{ K}) , \quad (1)$$

where U and I are the effective ultraviolet and infrared emissivities, r is the apparent angular distance of a grain from the central star, and T_* is the effective temperature of the central star. In deriving equation (1), it was assumed that the central star radiates like a blackbody, and the apparent visual magnitude was taken from Liller and Shao (1968). To estimate U/I, we assume that $\epsilon \propto \lambda^{-2}$ and take the ultraviolet wavelength to be 912 Å and the infrared wavelength 3 μm. Then $U/I \approx 10^3$, and

$$T_g = 350(r/1'')^{-1/2}(T_*/3 \times 10^4 \text{ K}) . \quad (2)$$

The central star of IC 418 is not much hotter than 3×10^4 (Kaler 1978*a*), and certainly the applicable angular radius is larger than 1″ (Fig. 2), so there is a serious difficulty in accounting for the high grain temperatures observed. One possibility is that the emissivity is a steeper function of wavelength ($\propto \lambda^{-2}$) than would be appropriate for small graphite particles. Even if T_* is as large as 5×10^4 K, U/I would have to be greater than 2×10^5, and if $\epsilon \propto \lambda^{-\alpha}$, then $\alpha \gtrsim 3.5$. We do not know whether grains with such properties exist. Moreover, if the actual grain temperatures are as high as the color temperatures, the grains might evaporate unless they are composed of highly refractory materials.

In view of the difficulty of heating grains to the high temperatures required, it is worthwhile to examine other possible mechanisms for producing the continuum radiation. Free-free radiation from interactions between hydrogen atoms and electrons ("H^- free-free") or hydrogen molecules and electrons ("H_2^- free-free") has been suggested as a mechanism for producing infrared radiation from certain stars (Milkey and Dyck 1973). The former process would not produce the correct wavelength dependence because of the presence of a bound state of H^-, but the latter process might be possible. Molecular hydrogen might be present in a region between expanding shock and ionization fronts in IC 418, perhaps in the same region where CO is found (Mufson, Lyon, and Marionni 1975; Black 1978). The H_2 would be heated, and free electrons would be available from the ionization of elements with lower ionization potentials than hydrogen by radiation from the central star. The absorption coefficients of H_2^- tabulated by Somerville (1964) were multiplied by a Planck function at various temperatures to find the appropriate temperature for IC 418. A temperature of 2500 K, reasonable for shock heating, produces an energy distribution in reasonable agreement with that of the excess radiation from IC 418. In order to estimate the densities required, it is necessary to determine the volume from which the radiation is emitted. One difficulty is that the region must be optically thick at radio wavelengths; otherwise 1.9 Jy of radio flux density would arise from the H_2^- alone. For unit optical depth to be reached in a distance equal to the nebular radius of 7×10^{16} cm (the distance of IC 418 is from Cudworth 1974), the required density product is $N_e N(H_2) \approx 10^{13}$ cm^{-6}, which seems too high to be consistent with the CO measurement (Mufson, Lyon, and Marionni 1975) and is much higher than the density calculated by Black (1978). Thus any form of thermal bremsstrahlung radiation seems unlikely to account for the excess 2 μm emission.

The excess continuum might be produced near the central star and scattered in the outer part of the nebula or in the surrounding neutral material. Scattering of visible light by particles has probably been detected in the nebula BD +30°3639 (Persson and Frogel 1973*a*), and large particles, as suggested by the shape of the silicon carbide feature in IC 418, would scatter efficiently at 2 μm. A serious difficulty with the scattering hypothesis is that the lack of detection of excess radiation from the vicinity of the central star (Willner, Becklin, and Visvanathan 1972) requires that the scattering optical depth be larger than unity. For this to be achieved within the radius of the nebula and without the grain mass exceeding the limit set by cosmic abundances requires the grain diameter to be less than 0.1 μm, even if the scattering efficiency is one. Such small grains would, however, have much smaller scattering efficiencies, and a highly nonuniform geometry is required. In particular, a concentration of scattering particles must be directly in our line of sight to the central star. This seems unlikely because of the observed brightness of the central star at optical wavelengths.

The excess 1.6–2.3 μm radiation from IC 418 is thus not satisfactorily explained. The previous suggestion of thermal emission requires grains with a very high ratio of ultraviolet to infrared emissivity, and no other acceptable suggestion has been made.

d) *Fine-Structure Lines*

The observed fluxes in the fine-structure lines of [Ne II], [S IV], [Ar II], and [Ar III] are given in Table 1. The observed fluxes of [S IV] and [Ar III] in NGC 6572 agree well with those reported by Gillett, Merrill, and Stein (1972) and Gillett, Forrest, and Merrill (1973); the [Ne II] flux from IC 418 agrees with that reported by Gillett and Stein (1969) if account is taken of the different absolute calibration.

The fluxes in the fine-structure lines can be used to derive ionic abundances. These ionic abundances are given in Table 3 and are almost independent of temperature and density. Calculations similar to those of Simpson (1975) were used with collision strengths from Osterbrock (1974), and the line fluxes were compared with radio fluxes listed by Higgs (1971); the adopted value for the optically thin 10 GHz radio flux from the entire nebula is shown in Table 3. Table 3 also gives the fractional abundance of each ion compared with the cosmic abundance of the element (Allen 1973), the ionization potential range for each ion, and similar information for Ne III from optical observations (Peimbert and Torres-Peimbert 1971).

The absence of S IV and low abundance of Ar III show that IC 418 is of very low excitation. The Ar III–to–Ar II ratio and the Ne III–to–Ne II ratio suggest that even lower excitation is present than in the model of Buerger (1973); only ~0.1 of these species appear to be doubly ionized.

NGC 6572 is of higher excitation than IC 418, as shown by the presence of [Ar III] and [S IV] and expected from the temperature of its central star (Kaler 1976*b*, 1978*a*). One surprising fact is that there is no detectable [Ne II] emission, although that ion occurs in a range of ionization potentials that includes Ar III, which is seen (Table 3). Optical observations tabulated by Kaler (1976*a*) together with atomic parameters (Osterbrock 1974) suggest that the dominant ionization states are in fact Ne III and Ar III, even though these ions have different ranges of ionization potential. Such an effect was found in a model of IC 4593 by Buerger (1973), but this nebula has a considerably cooler central star than NGC 6572 (Kaler 1976*b*). Kaler (1978*b*) has found that only about half of the argon in planetary nebulae can be in either the Ar II or Ar III state, contrary to the behavior of oxygen and neon. R. J. Gould (private communication) has pointed out to us that it is the photoionization and recombination rates, rather than simply the ionization potentials, that determine the ionization balance. Evidently the relative rates for argon and neon are different, and it appears that abundances of unobserved argon ions derived solely on the basis of abundances of other ions having similar ionization potentials must be considered questionable.

IV. SUMMARY

The spectra of IC 418 and NGC 6572 show an emission plateau from 10.5 to 13 μm. We suggest that this feature is due to large silicon carbide grains. It is therefore suggested that the grains are carbon-rich,

TABLE 3

DERIVED IONIC ABUNDANCES

Line	Ionization Potential Range	NGC 6572 N(ion)/N(H II)	NGC 6572 N(ion)/N(cosmic)	IC 418 N(ion)/N(H II)	IC 418 N(ion)/N(cosmic)
[Ar II] λ6.99	16–28 eV	$< 2.9 \times 10^{-6}$	< 0.46	3.0×10^{-6}	0.48
[Ar III] λ8.99	28–41 eV	2.2×10^{-6}	0.35	6.1×10^{-7}	0.10
[Ne II] λ12.81	22–41 eV	$< 8 \times 10^{-6}$	< 0.10	6.1×10^{-5}	0.74
[S IV] λ10.51	35–47 eV	3.4×10^{-6}	0.16	$< 6 \times 10^{-7}$	< 0.03
[Ne III][a]	41–64 eV	1.4×10^{-4}	1.7	4.8×10^{-6}	0.06
Adopted 10 GHz radio flux		1.29 Jy		1.62 Jy	

[a] Peimbert and Torres-Peimbert 1971.

and the emission feature observed at 3.3 μm is due to a grain species or molecular constituent containing C–H bonds. Other emission features previously associated with that at 3.3 μm are weak or absent, and it appears that these features should be associated with the 3.4 μm wing rather than with the 3.3 μm feature itself.

The short wavelength excess emission in IC 418 appears to form a true continuum between 2 and 4 μm. This emission has too high a color temperature to be easily understood as direct thermal emission from grains, but no other plausible mechanism has been suggested.

The Ar^{++} to Ne^{+} abundance ratio is extraordinarily high in NGC 6572, although the ionization potential range of Ne^{+} includes that of Ar^{++}. The low excitation of IC 418 is confirmed by the large ratio of singly to doubly ionized argon and neon.

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B. JONES: School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455

R. C. PUETTER and S. P. WILLNER: Department of Physics, C-011, University of California, San Diego, La Jolla, CA 92093

R. W. RUSSELL: Astronomy Department, Cornell University, Space Science Building, Ithaca, NY 14853

B. T. SOIFER: Downes Laboratory, 320-47, California Institute of Technology, Pasadena, CA 91125