OBSERVATIONS OF DUST IN PLANETARY NEBULAE

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1. INTRODUCTION

This review summarises those observations which relate to the existence of dust in planetary nebulae. The most direct evidence for dust, namely infrared emission by grains, is considered in Section 2. Section 3 describes a variety of optical and ultraviolet observations which bear more indirectly on the properties of the dust, while Section 4 discusses the power sources of the observed infrared emission. The peculiar nebulae A 30 and A 78 are considered in Section 5, and Section 6 concludes with a discussion of the various infrared features which have been observed in emission from planetary nebulae.

2. INFRARED PHOTOMETRIC STUDIES OF PLANETARY NEBULAE

Since the discovery by Gillett, Low and Stein (1967) of 10 μm emission from NGC 7027, which was greatly in excess of the expected free-free and line fluxes, the study of dust in planetary nebulae has virtually been a study of dust in NGC 7027. Although a variety of observational data are now available for other nebulae, they still lack the wealth of detail afforded by the brightness of NGC 7027 in the infrared. Table 1 summarises the published ground-based photometry of planetary nebulae.

Krishna Swamy and O'Dell (1968) interpreted the infrared continuum from NGC 7027 in terms of emission from small graphite particles heated by resonantly trapped Lyman-α photons. They were not able to distinguish whether the grains were inside the ionized zone or in a surrounding neutral shell. They suggested that the grains could have originated in the envelope of a precursor red giant star, which is now the accepted explanation. Terzian and Sanders (1972) calculated the expected IR flux distributions under the assumption that the grains resided in a neutral shell and predicted mean grain temperatures of ∿85 K, with fluxes peaking at ∿35 μm. The 10-18 μm observations of Cohen and Barlow (1974) did not seem to support the prediction,

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TABLE 1: GROUND-BASED INFRARED PHOTOMETRY OF PLANETARY NEBULAE

OBSERVERS	REFERENCE	NUMBER OF PN DETECTED AT EACH WAVELENGTH (μm)						OBJECT NAME(S)
		1.6	2.2	3.5	10	11	20	
Gillett, Low, Stein	1967,Astrophys.J.,149,L97				1	1		NGC 7027
Woolf	1969,Astrophys.J.,157,L37					5		
Gillett, Stein	1970,Astrophys.J.,159,817			2		2		NGC 6572, BD+30^{o}3639
Neugebauer, Garmire	1970,Astrophys.J.,161,L91			1	1			NGC 7027
Gillett, Knacke, Stein	1971,Astrophys.J.,163,L57			3		3		IC 4997, VV8, FG Sge, Sh 2-71
Gillett, Merrill, Stein	1972,Astrophys.J.,172,367					15	3	
Willner, Becklin, Visvanathan	1972,Astrophys.J.,175,699	11	15	8				
Persson, Frogel	1973,Astrophys.J.,182,503	19	24	11				
Danziger, Frogel, Persson	1973,Astrophys.J.,184,L29	1	1	1	1		1	NGC 6302
Allen	1973,M.N.R.A.S.,161,145	5	5					
Becklin, Neugebauer, Wynn-Williams	1973,Astrophys.Lett.,15,87				1		1	NGC 7027
Khromov	1974,Sov.Astr.,18,195	15	5					
Webster, Glass	1974,M.N.R.A.S.,166,491	2	2	2				He 2-113, CPD-56^{o}8032
Allen, Glass	1974,M.N.R.A.S.,167,337	63	100	28				
Allen	1974,M.N.R.A.S.,168,1	7	15	8	2	2	2	
Cohen, Barlow	1974,Astrophys.J.,193,401		10	16	51	15	40	
Cohen, Barlow	1975,Astrophys.Lett.,16,165	1	1	1	1			NGC 2346
Cohen	1975,M.N.R.A.S.,173,489			1	1	1	1	He 2-113
Dyck, Simon	1976,P.A.S.P.,88,738						2	NGC 7027, BD+30^{o}3639
Cohen, Hudson, O'Dell, Stein	1977,M.N.R.A.S.,181,233	2	2	2				A 30, A 78
Cohen, FitzGerald, Kunkel, Lasker, Osmer	1978,Astrophys.J.,221,151	1	1	1	1	1	1	Mz 3
Cohen, Barlow	1980,Astrophys.J.,238,585				23	18	20	

yielding mean colour temperatures of ∿190 K. It later became clear that broadband ($\Delta\lambda \sim 5$ μm) observations of planetary nebulae at 10 μm can significantly overestimate true continuum levels due to the presence of numerous emission lines and features in this region, thus yielding too high 10-18 μm colour temperatures. More importantly though, airborne far-infrared observations by Telesco and Harper (1977), McCarthy, Forrest and Houck (1978) and Moseley (1980) have shown that (1) the IR energy distributions of most planetaries do in fact peak near 30 μm, (2) the flux distributions shortward of the peak cannot be fitted by single temperature grain models and therefore (3) ground-based 10-20 μm observations sample a hotter dust component than 30-100 μm observations.

Telesco and Harper (1977) found that their far-infrared data for NGC 7027 could be fitted by a 95 K blackbody with a λ^{-2} emissivity. Classical Mie theory calculations predict such an emissivity law for small graphite particles. McCarthy et al (1978) obtained 15-40 μm spectrophotometry of NGC 7027 and found that a 90 K blackbody with λ^{-2} emissivity yielded the best fit. Shortward of 20 μm, the 90 K spectrum left an excess of smooth continuum, establishing the presence of hotter dust. The 90 K spectrum, which makes only a small contribution at 10 μm, accounts for 68% of the total infrared flux. Of the remaining 32%, 3% is emitted in the unidentified features between 3.3 and 11.3 μm and 29% is emitted by hotter dust. Kwok (1980) has fitted this excess short wavelength continuum with a λ^{-2} emissivity, 230 K blackbody spectrum.

Moseley (1980) has observed thirteen planetaries at four wavelengths between 37 and 108 μm. Most of the flux distributions were similar to that of NGC 7027, despite the fact that the range of nebular densities and ages was large. The mean colour temperature was 80 K (for λ^{-2} emissivity). Figure 1 shows the IR flux distributions of some of the planetary nebulae observed by Moseley. IC 418 was found to have a more sharply peaked flux distribution than the other nebulae. Recent spectrophotometric observations by Forrest, Houck and McCarthy (1981) have shown that this was due to the presence of a strong emission feature in Moseley's 28-52 μm passband.

Many attempts have been made to derive the masses of emitting dust in planetary nebulae. As pointed out by Panagia (1975) and Mathis (1978), to do this accurately requires a knowledge of the composition and size distribution of the emitting particles, since differently sized grains will have different emissivities and temperatures in the same radiation field. Masses derived assuming a single grain temperature and size are thus susceptible to large errors, especially at shorter wavelengths. The errors should decrease at longer wavelengths where emissivities approach the Rayleigh limit and the cool grain component dominates. Telesco and Harper (1977) have shown that for grains with a ν^n emissivity, the total mass of IR emitting dust can be derived from the relation:

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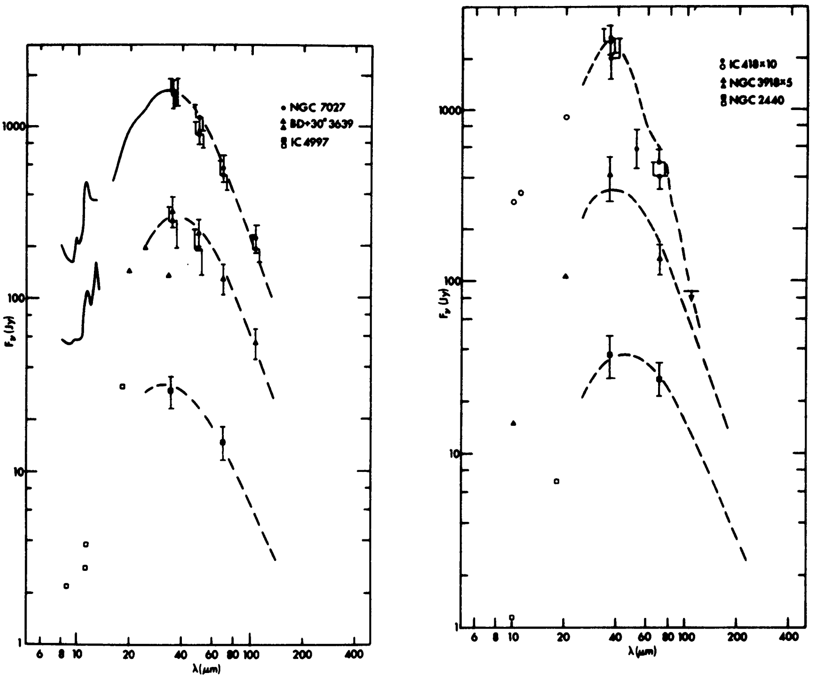

Figure 1. Infrared flux distributions of six planetary nebulae in the form of F_ν versus λ. Dashed lines indicate fits to the far-infrared photometric points (Figure from Moseley 1980).

$$M_d = \frac{a\rho_d}{Q(\nu_{max})} \cdot \frac{\nu_{max}^{n} L_{IR}(\lambda > 17\mu m)}{K(n) T_d^{4+n}} \qquad (1)$$

where a and ρ_d are the radius and mean density of the emitting grains of temperature T_d which have an emissivity $Q(\nu_{max})$ at the peak of the infrared energy distribution. K(n) is a numerical constant for each value of n and L_{IR} is the luminosity of the dominant grain component. Moseley (1980), by observing out to 108 μm, was able to make use of the expression derived by Hildebrand et al (1977) in which grains are assumed to emit in the Rayleigh-Jeans limit at long enough wavelengths:

$$M_d = \frac{a\rho_d}{Q(\nu)} \cdot \frac{4D^2 F_\nu}{3B(\nu, T_d)} \propto \frac{a\rho_d}{Q(\nu)} \cdot \frac{L_\nu}{T_d} \qquad (2)$$

where D is the distance of the nebula. This method is less sensitive to the grain temperature, but an estimate of the emissivity is still required.

The observed form of the infrared spectrum of NGC 7027 suggests an n=2 grain emissivity, for which graphite seems appropriate. However, Forrest, McCarthy and Houck (1980) have noted that the recent determination of the far-infrared constants of graphite by Philipp (1977) would,

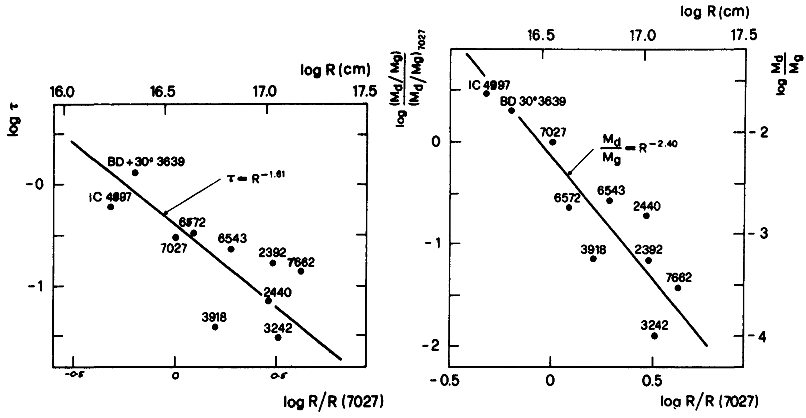

Figure 2. Left hand figure: the UV optical depth of internal dust in ten planetary nebulae versus nebular radius. Right hand figure: the dust-to-gas ratio for the ten planetary nebulae versus nebular radius (Figures from Natta and Panagia 1981).

if appropriate for small grains, predict an n=3 emissivity beyond 20 μm. On the other hand Koike, Hasegawa and Manabe (1980) have experimentally found an n=1 emissivity for small amorphous carbon grains.

In order to overcome the uncertainty associated with the absolute values of far-infrared grain parameters, Natta and Panagia (1981) have carried out a differential analysis of the planetary nebulae observed by Moseley. The analysis, based on the methods they had already applied to HII regions, assumed the dust to have an internal UV extinction, τ_{int}, in the ionized zone. Their results are shown in Figure 2. They found that the dust column density, τ_{int}, decreased with nebular radius as $R^{-1.6}$ (Figure 2). The gas column density, on the other hand, decreased as $R^{-0.46}$, similar to the $R^{-0.5}$ law expected for ionization bounded nebulae, thus providing evidence for increasing dust depletion with increasing nebular age. The absolute values of τ_{int} for NGC 7027 and NGC 7662 were 0.3 and 0.14, similar to the values derived from UV observations of CIV λ1549 (see section 3.4). The dust-to-gas ratio was found to decrease as $R^{-2.4}$ (Figure 2). Evidence was also found for a decrease in the mean grain radius with increasing nebular radius. Natta and Panagia noted that the low values of τ_{int} which they derived for most nebulae implied that dust does not affect the ionization structure of planetary nebulae significantly. They also argued that the low derived values of M_d/M_{gas} ($\leq 3\times10^{-4}$) for the older nebulae implied that they could not enrich the dust content of the interstellar medium, but would dilute it instead.

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3. OTHER OBSERVABLE EFFECTS OF DUST IN PLANETARY NEBULAE

3.1 Red/blue line profile asymmetries

Osterbrock (1974) pointed out that if significant internal dust existed in the ionized region of a planetary nebula, it would produce asymmetric emission line profiles, since the red wing, originating from the far side of the nebula, would suffer more extinction than the blue wing. Since an asymmetric distribution of gas could give rise to spurious results if only a single profile was analysed, Osterbrock instead compared the profiles of three different Balmer lines. For normal extinction laws, the effect of internal extinction would be most pronounced on the profile with the shortest rest wavelength. However the Hα, Hβ and Hγ lines of NGC 7027 showed no noticeable differences in their profiles and Osterbrock set a conservative upper limit of $\tau(H\beta) < 0.6$.

Hicks, Phillips and Reay (1976) analysed the less thermally broadened [OIII] λ5007 profile at various points on NGC 7027. A red/blue asymmetry was found, consistent with a non-uniform gas distribution or $\tau_{int}(\lambda=5007) \sim 0.34$. However, Hicks et al also pointed out that the effects of internal extinction could be mimicked by a non-uniform distribution of external dust across the face of an inclined spheroidal nebula, preferentially extinguishing the emission from one side (and velocity). NGC 7027 is known to have just such an asymmetric distribution of external dust since the 5 GHz radio contours of Scott (1973) are very symmetric, whereas the optical image is cut off on the southern side. The spatial distribution of extinction across NGC 7027 has been mapped by Atherton et al (1979). The external dust appears to be associated with the dense molecular CO envelope discovered by Mufson, Lyon and Marionni (1975).

Doughty and Kaler (1982) have analysed the extensive coudé plate collection for seven planetaries observed by O. C. Wilson. They compared both short and long wavelength lines in order to eliminate the effects of asymmetric gas distributions. For NGC 7027 they derived $\tau(H\beta) = 0.15$, under the assumption that the dust is internal.

3.2 Scattered light continua

Galactic Population I HII regions have long been known to exhibit optical continua dominated by dust-scattered starlight (e.g. O'Dell and Hubbard 1965) and in the UV the observed ratio of scattered light to nebular continuum is even larger (e.g. Perinotto and Patriarchi (1980) for the Orion Nebula). To my knowledge, no continuum in excess of that attributable to atomic processes has ever been observed from the ionized region of a planetary nebula.

Page (1936) studied the continuous and Balmer line spectrum of NGC 7662 on plates taken with the DAO 72" reflector. He found that the nebular continuum in the 3900-4800 Å region was much stronger than the

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predicted Paschen continuum and suggested that starlight scattered by dust particles within the nebula was responsible. This represents one of the first suggestions of the existence of dust in planetary nebulae. However, allowance for the existence of a hydrogen two-photon continuum later removed the discrepancy (Seaton 1955). The line to continuum ratios derived by Page agree to within 20% with the ratios predicted using the nebular parameters of Harrington et al (1982).

Persson and Frogel (1973) observed the Hβ line to continuum ratio in BD+30^{o}3639, one of the intrinsically strongest infrared emitters amongst planetary nebulae. Their initial results indicated the detection of a dust-scattered continuum (corresponding to τ_s(Hβ) $\sim$ 0.07) but later analysis, published as an erratum, weakened the evidence.

Telesco and Harper (1977) noted the existence of a faint Hβ halo in electronographic maps of NGC 7027 made by Coleman, Reay and Worsick (1975) and suggested that the halo was due to light scattered by dust in the neutral shell surrounding the ionized zone. A deeper exposure in Hα by Atherton et al (1979) has shown the reflection nebula to have a major axis diameter of $\sim$50 arcsec (versus $\sim$13 arcsec in the radio), which is comparable to the diameter of the CO emitting region mapped by Mufson et al (1975). To test this interpretation, optical polarisation maps would be very useful. It would also be interesting to obtain polarisation measurements of the giant haloes surrounding many planetary nebulae, in order to see whether the haloes emit intrinsically or are due only to the scattering by dust of light from the nebular cores. Such dust could have been produced during the mass loss phase of a progenitor red giant star.

3.3 Abnormal extinction laws

The infrared continuum emission from planetary nebulae has often been attributed to graphite grains, which have also been proposed to be responsible for the interstellar 2200 Å extinction feature. Pottasch et al (1977) investigated the strength of the 2200 Å feature towards 30 planetary nebulae using ANS photometric data. The extinctions that they derived from the 2200 Å feature, assuming a standard UV extinction law, were in very good agreement with the extinctions derived from radio-Hβ fluxes, with no evidence for an abnormal component. They concluded that the infrared emitting dust inside planetary nebulae did not have large UV optical depths. Adams and Barlow (these Proceedings) have measured the strength of the 2200 Å feature towards four planetary nebulae which show 10 μm silicate emission features. They found the 2200 Å strengths to be weaker than predicted by the radio-Hβ extinctions, consistent with some of the reddening being due to local silicate dust without a corresponding graphite component.

On the basis of a radio map published by Sistla and Kaftan-Kassim (1976) and its comparison with a Hβ map by Phillips, Reay and Worsick (1979), it has been suggested that the region around the central star of IC 3568 is more highly reddened than the nebula as a whole. However,

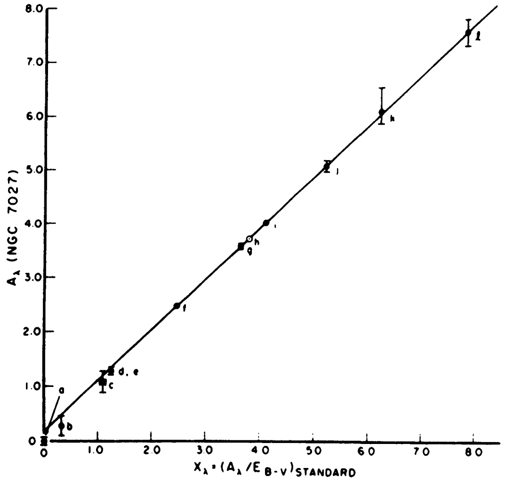

Figure 3. Extinction, A_λ, of NGC 7027 in magnitudes, deduced from radio continuum and HI and HeII recombination line measurements, plotted against standard interstellar extinction at the same wavelengths (Figure from Seaton 1979).

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from an analysis of UV, optical and radio data, Harrington and Feibelman (1982) have found no evidence for a difference in the reddening suffered by the central star compared with the nebular lines.

Seaton (1979) has analysed the relative intensities of HI and HeII recombination lines emitted by NGC 7027 in the infrared, optical and ultraviolet. He found remarkable agreement between the standard Galactic extinction law and the law derived for NGC 7027 (Figure 3). The straight line in Figure 3 does not pass through the origin and Seaton showed that this could be explained by heavier extinction over a fraction of the nebula, with the same standard extinction law. Since the ionized nebula is believed to be carbon-rich (Section 6), as by extension are the surrounding neutral shell and dust, it might seem surprising that the extinction law towards NGC 7027 appears to be normal, because interstellar dust is thought to consist of a mixture of both graphite and silicate grains (e.g. Mathis, Rumpl and Nordsieck, 1977). However, Kwok (1980) has pointed out that if, prior to PN envelope ejection, a red giant star goes from an oxygen-rich mass loss phase producing silicate grains to a carbon-rich phase producing graphite grains, the silicate grains would be too far out and too cool to emit appreciably in the infrared during the planetary nebula phase. Since red giant stars are thought to be the main source of interstellar dust, it might not, therefore, be surprising to find a normal reddening law through the envelope surrounding NGC 7027.

3.4 Depletion of UV resonance lines by internal dust

Bohlin, Marionni and Stecher (1975) obtained the first UV spectrum of NGC 7027 and found that the CIV λ1549 resonance doublet was a factor of three weaker, relative to CIII] λ1909, than predicted by model nebula calculations. They ascribed the discrepancy to dust absorption of the resonantly scattered CIV photons and derived a radial dust optical depth within the ionized zone of $\tau_d(1549) \sim 0.2$, using the resonance line transfer results of Panagia and Ranieri (1973). Their nebular model had an ionized hydrogen column density of $N_H = 1.9 \times 10^{21}$ cm^{-2} and they noted that this column density, combined with a normal interstellar reddening law and colour excess ratio, $N_H/E_{B-V} = 5.4 \times 10^{21}$

$cm^{-2}\ mag^{-1}$, would predict $\tau_d(1549) = 2.6$, so that the dust within the ionized zone must be depleted by a factor of ten if it has normal reddening characteristics.

Harrington et al (1982) have carried out a very extensive analysis of the optical and UV spectrum of NGC 7662. By comparing their model predictions with the relative strengths of CIII λ2297 and CIV λ1549, they inferred that CIV λ1549 was depleted by a factor of three by internal dust (see Seaton, these Proceedings). Using the resonance line transfer results of Hummer and Kunasz (1980), along with the CIV line optical depths from their own model, they derived an internal dust optical depth of $\tau_d(1549) = 0.08\text{-}0.13$. These results may imply that a $\tau_d(1549)$ of only 0.1 is required to explain the depletion of CIV in NGC 7027, but a more extensive nebular analysis is required. The hydrogen column density in Harrington et al's model of NGC 7662 was $6 \times 10^{20}\ cm^{-2}$ which, with a normal interstellar colour excess ratio and reddening law, would predict $\tau_d(1549) = 0.8$. Thus the dust in the ionized zone of NGC 7662 must also be severely depleted compared to interstellar ratios if it has normal reddening characteristics.

Clavel, Flower and Seaton (1981) have derived $\tau_d(1335) = 0.08$ for the ionized zone of IC 418, from an analysis of the relative intensities of the CII λ1335 and λ4267 lines (see Seaton, these Proceedings).

4. THE ENERGETICS OF DUST EMISSION FROM PLANETARY NEBULAE

Following the initial suggestion by Krishna Swamy and O'Dell (1968), the absorption by dust of resonantly trapped Lyman-α photons has often been suggested to be the power source for the infrared emission from planetary nebulae. For example, Cohen and Barlow (1974, 1980) proposed that Lyman-α absorption dominated the infrared energetics of the medium and low density planetaries in their survey.

Becklin, Neugebauer and Wynn-Williams (1973) mapped NGC 7027 at 10 μm (broadband) with a 1.8 arcsec beam and found that the infrared contours closely followed those of the 5 GHz map made by Scott (1973). They inferred that the emitting dust was uniformly mixed with the ionized gas. Since their derived ratio of total infrared to Ly-α flux, $L_{IR}/L_{Ly\text{-}\alpha}$, was much greater than unity, they argued that the dust was heated by direct absorption of stellar continuum photons shortward of the Lyman limit, with $\tau_d(UV) \sim 1$. This is much larger than the value of τ_d implied by the depletion of CIV λ1549.

Telesco and Harper (1977) measured the total IR flux of NGC 7027 to be 2.4×10^{-7} ergs $cm^{-2}\ s^{-1}$. With $S_\nu = 6.3$ Jy at 5 GHz and $T_e = 1.35 \times 10^4$ K, the relation of Rubin (1968) implies $L_{IR}/L_{Ly\text{-}\alpha} = 3.4$. Telesco and Harper noted that this ratio could be achieved if dust absorbed half of the stellar continuum photons plus all the Ly-α photons. They noted that, alternatively, the IR emission could be powered by the diffuse nebular radiation emitted longward of 912 Å, on the basis of the

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flux predictions of nebular models. With the availability of IUE data, it is now possible to investigate this case more fully. Table 2 presents the energy and photon budget of NGC 7027 between 912 Å and 5100 Å.

TABLE 2: ENERGY AND PHOTON BUDGET OF NGC 7027

Spectral Component	λ (Å)	$I_{Dered}-I_{Obs}$ ($\times 10^{-9}$ ergs cm^{-2} s^{-1})	$N_{Photons}$ (cm^{-2} s^{-1})
HI Ly-α	1216	70	4300
CIV	1548,1550	28.2 × 3	6600
CIII]	1909	19.3	1900
[OIII]	4959,5007	32.3	8100
Other lines	1200-5000	35.7	4600
Nebular continuum	1200-5000	20.8	2600
	Total:	262.7	28100

The observed UV and optical line fluxes have been taken from Perinotto, Panagia and Benvenuti (1980) and Kaler et al (1976). They have been dereddened by C(Hβ) = 1.43 (Seaton 1979), corresponding to A_V = 3.1, and the observed fluxes subtracted to give the total flux available for heating dust (column 3). The flux of CIV λ1549 was multiplied by three to allow for resonance line depletion. The nebular continuum was calculated using $n_e = 5.9 \times 10^4$ cm^{-3} and $T_e = 1.35 \times 10^4$ K. The Hβ flux and He^+ and He^{2+} abundances were taken from Miller and Mathews (1972). Column 4 gives the corresponding photon fluxes. The available dereddened nebular flux of 2.6×10^{-7} ergs cm^{-2} s^{-1} can comfortably supply the 2.4×10^{-7} ergs cm^{-2} s^{-1} observed in the infrared. One can therefore envisage a two-component model, whereby warm dust in the ionized region, with τ_d(UV) ∿ 0.1-0.2, is heated by Ly-α and CIV resonance photons, while colder dust in the surrounding neutral shell is heated by the remaining nebular photons. In this model the cool component could be identified with the $\lambda^{-2} B_\lambda$(90 K) dust, which supplies 70% of the total IR luminosity, while the warm dust in the ionized zone could be identified with the $\lambda^{-2} B_\lambda$(230 K) component, which has been shown by Kwok (1980) to fit the remaining continuum. Since the 90 K dust will make only a very small contribution at 10 μm, the dust continuum at 10 μm would be expected to have the same spatial distribution as the radio emission, in agreement with the observations of Becklin et al (1973). If the flux of Ly-α and CIV photons were depleted by a factor of 2.3 in the ionized region, instead of by the factor of 3 assumed in Table 2, the total energy available for powering dust emission would be 2.4×10^{-7} ergs cm^{-2} s^{-1}, with 30% absorbed in the HII region, exactly in keeping with the proportions derived observationally.

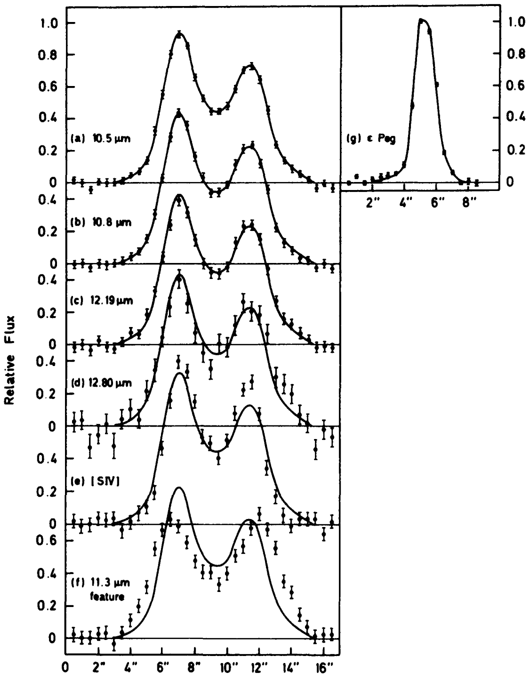

Figure 4. Spatial profiles along the minor axis of NGC 7027 at 4 continuum wavelengths (a - d), in the [SIV] line (e), and the 11.3 μm emission feature (f). The system response to a stellar source is shown in (g). Figure taken from Aitken and Roche (1982b).

Natta and Panagia (1981) have constructed a model in which the total infrared luminosity of NGC 7027 is explained by an optical depth $\tau_d(UV) = 0.3$ within the ionized region alone. In their model, the far infrared emission arises from large, cool grains in the ionized zone, while the 10 μm emission comes from smaller and hotter grains in the same region. One way to discriminate between the two alternative models might be to make an accurate estimate of $\tau_d(1549)$, while comparing the total infrared luminosity with the integrated stellar luminosity deduced from a Stoy-type analysis. Another would be to compare the spatial distribution of dust emission at 10 μm and 35 μm, since the cool component should originate outside the ionized zone according to the two-zone model.

Aitken and Roche (1982b) have used a grating spectrometer to make spatial scans along the minor axis of NGC 7027 simultaneously in 30 wavelength channels between 10 and 13 μm, with a FWHM beamwidth of 1.5 arcsec. They also mapped the nebula in the 10.5 μm [SIV] line and in the adjacent continuum. The spatial profiles which they obtained at 6 wavelengths are shown in Figure 4. The top 4 profiles of the continuum, at wavelengths between 10.5 and 12.8 μm, are identical within the errors, showing that there is no pronounced temperature gradient within the emitting dust at these wavelengths. Aitken and Roche argued that this supported heating by resonantly trapped photons, rather than by direct absorption of starlight. Their 10.25 μm continuum map had the same FWHM as the 5 GHz radio map of Scott (1973), while the [SIV] map FWHM was 1 arcsec smaller. On the other hand, the unidentified 11.3 μm dust feature (see Section 6) has a FWHM 1.5 arcsec larger than that of the continuum (Figure 4f) and clearly originates in the neutral shell surrounding the ionized zone. Can this narrow dust shell be identified with the dominant 90 K component? Kwok (1980) has shown that if the dust in the surrounding neutral shell has an r^{-2} density distribution and a λ^{-2} emissivity, then the 20-50 μm emission will be sharply

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peaked just outside the boundary of the ionized zone. To test this model, high spatial resolution ground-based observations are needed, with simultaneous mapping at 10, 20 and 35 μm. Non-simultaneous maps are of little use since an increase in size from 10 to 35 μm of a few arcseconds could not be reliably proven or disproven.

Since NGC 7027 is unusual in respect of the amount of material surrounding it, one might ask if a similar two-component model is appropriate for explaining the infrared luminosities of other planetary nebulae. Moseley (1980) has measured the total IR fluxes of eleven other nebulae. As some of the values of $L_{Ly-\alpha}$ used by Moseley were incorrect, corrected $L_{IR}/L_{Ly-\alpha}$ ratios are listed in Table 3. With the exception of NGC 7662 (Harrington et al 1982) the values of $L_{Ly-\alpha}$ used in Table 3 have been calculated using the relation of Rubin (1968) and are not adjusted for hydrogen recombinations which result in two-photon emission. For the lower density nebulae ($n_e < 10^4$ cm^{-3}) this correction would increase $L_{IR}/L_{Ly-\alpha}$ by a factor of ∿1.4.

TABLE 3: IR DATA FROM MOSELEY (1980)

Planetary Nebula	$L_{IR}/L_{Ly-\alpha}$	$T_d(n=2)$
BD+30^{o}3639	7.9	80
IC 4997	4.3	80
NGC 7027	3.4	90
NGC 7662	2.7	80
NGC 6543	2.1	75
NGC 6572	2.1	90
NGC 2392	1.5	70
IC 418	1.4	
NGC 2440	1.0	65
NGC 3918	0.9	85
NGC 3242	0.4	85

The highest value of $L_{IR}/L_{Ly-\alpha}$ (= 7.9) belongs to BD+30^{o}3639, whose central star has a spectral type, WC9, for which $T_{eff} \simeq 3 \times 10^4$ K. At this effective temperature 80% of the stellar radiation is emitted longwards of 912 Å, while 12% of the stellar flux will be reradiated as nebular Ly-α photons, in the absence of direct absorption of ionizing starlight by dust. Therefore, if all of the stellar flux longwards of 912 Å was absorbed by dust in a neutral shell, accompanied by the absorption of Ly-α photons in both the ionized and neutral zones, the ratio $L_{IR}/L_{Ly-\alpha}$ would be 7.8.

Moseley finds IC 418 to have a total infrared flux of 3×10^{-8} ergs cm^{-2} s^{-1}. The total (dereddened - observed) flux of IC 418 between 912 Å and 2000 Å is 5×10^{-8} ergs cm^{-2} s^{-1}, with 42% in Ly-α and 58% in the stellar continuum. Here, the power requirments can be met without requiring a large fraction of the overall extinction to be local.

All of the planetaries mentioned above are fairly high density ($n_e \gtrsim 10^4$ cm^{-3}), ionization bounded nebulae, for which it is reasonable to expect a surrounding neutral shell. However, at lower nebular densities planetary nebulae will become optically thin in the Lyman continuum and neutral shells will not exist. NGC 7662 is probably such a nebula, for which Moseley found a total infrared flux of 1.2×10^{-8}

ergs cm^{-2} s^{-1}. The (dereddened - observed) flux between 912 Å and 5000 Å is 1.17×10^{-8} ergs cm^{-2} s^{-1} and so could in principle power the infrared emission (Ly-α 34%, CIV 5%, other lines 22%, continuum 39%). However, this would require virtually all of the reddening towards NGC 7662 to be local and would conflict with the analysis of Harrington et al (1982) who found the hydrogen Lyman continuum to be optically thin. Harrington et al showed instead that the optical depth of dust inside the ionized zone, $\tau_d(1549) = 0.1$, could explain the observed infrared emission by absorbing two-thirds of the nebular Ly-α and CIV λ1549 photons, along with 10% of the overall stellar continuum, yielding a flux of 1.3×10^{-8} ergs cm^{-2} s^{-1}(Ly-α 20%, CIV 13%, stellar continuum 67%). Although there is a problem in that 95% of the nebular Hβ flux from NGC 7662 is emitted in a 27 arcsec aperture versus only 50% of the total infrared flux, this may be due to inaccuracies in the infrared data. It seems clear that the far-infrared emission from the older density bounded nebulae originates from dust inside the observed ionized zones.

It is suggested in Section 6, for other reasons, that carbon grains are present in the neutral zone around carbon-rich planetary nebulae (C/O > 1) but are destroyed while passing through the advancing ionization-dissociation fronts, leaving only less abundant grain materials, such as iron, present in the ionized zones. This would explain the decreasing dust-to-gas ratios found by Natta and Panagia (1981) in the progression from young ionization bounded nebulae to older density bounded nebulae and would also explain the severe dust depletions in the ionized zones of both types of nebulae implied by the low derived values of $\tau_d(1549)$ (Section 3.4). According to this scenario, in young, dense, carbon-rich nebulae the far-infrared continuum would be emitted by carbon grains in the neutral shell, while the 10 μm continuum would come from iron, or other grains in the ionized region. In older, density-bounded nebulae these grains within the ionized zone would provide all the infrared emission. Grains in the ionized zone, with a λ^{-2} emissivity, heated solely by trapped resonance line radiation whose energy density is proportional to n_e^2, will have $T_d^6 \propto n_e^2$. Thus the T_d = 230 K component in the ionized zone of NGC 7027 would have T_d = 85 K if the density was reduced from $n_e = 6 \times 10^4$ cm^{-3} to $n_e = 3 \times 10^3$ cm^{-3}, a value typical of the less dense planetary nebulae in Moseley's sample.

Shields (1978) has shown that the observed depletion of iron by a factor of 25 over cosmic values in NGC 7027 would, if the iron was tied up in grains, give $\tau_d(1549) \sim 0.1$, which is sufficient to explain the reduction in CIV λ1549 intensity over computed values and to give agreement with the depleted dust-to-gas ratio deduced by Bohlin et al (1975). Similarly, Harrington et al (1982) noted that their derived $\tau_d(1549)$ for NGC 7662 could be explained by a cosmic abundance of iron locked up in grains. Scaling the ionized hydrogen column density in their model of NGC 7662 up to the column density in the Shields (1978) model of NGC 7027 gives $\tau_d(1549)$ = 0.12-0.20 for NGC 7027.

For a constant dus-to-ionized gas ratio, n_d/n_H, the dust optical depth $\tau_d(II)$ within the ionized radius R_{II} of a linearly expanding spherical nebula will be given by $\tau_d(II) \propto n_d R_{II} \propto R_{II}^{-2}$, if the nebula is density bounded. In an ionization bounded nebula, recombinations balance ionizations and $n_H^2 R_{II}^3$ is constant, so $\tau_d(II) \propto R_{II}^{-1/2} \propto n_H^{1/3}$. Since NGC 7662, with $n_H = 3 \times 10^3$ cm^{-3}, is only just density bounded (Harrington et al 1982), we can extrapolate the latter relation backwards to predict that only at densities in excess of a few times 10^5 cm^{-3} should dust compete significantly with gas for ionizing stellar photons.

5. A 30 AND A 78

A 30 and A 78 are a pair of large, low surface brightness planetary nebulae with OVI central stars. Cohen and Barlow (1974) found that both nebulae exhibited strong 10 and 20 μm dust emission from their central zones with colour temperatures of ∿140 K. A 30 was found to have a FWHM at 10 and 18 μm of ∿25 arcsec in both NS and EW directions, compared to an optical diameter of 130 arcsec. Since there were no known optical nebulosities on existing photographs of these nebulae which corresponded to the extent of the dust emission, Cohen and Barlow suggested that the dust had condensed in the outflowing stellar winds from the OVI central stars.

Cohen et al (1977) made multiaperture observations of A 30 and A78 between 1.6 and 3.5 μm and found significant emission from hot dust grains (T_d ∿ 1000 K). The angular diameters at 2.3 and 3.5 μm were similar to those found by Cohen and Barlow at 10 and 18 μm, but the infrared spatial distribution was not in agreement with that predicted by an R^{-2} stellar wind density distribution. The excess fluxes were instead linearly proportional to aperture area.

Moseley (1980) found A 30 to have an angular diameter of ∿25 arcsec at 37 μm, with the dominant dust component having a colour temperature of 60 K for a λ^{-2} emissivity. Moseley noted that the dust temperature and total infrared luminosity of A 30 was similar to those of the high surface brightness planetaries in his sample, implying that the amount of dust in the central 15 arcsec of A 30 was comparable to the total amount of dust in a typical high surface brightness nebula.

A first step towards an understanding of the origin of the centrally concentrated dust in A 30 and A 78 came with the independent discovery by Jacoby (1979) and by Hazard et al (1980) of centrally condensed knots of strong [OIII] emission in both nebulae. The major axis diameters of the central nebulosities, at 24 and 23 arcsec in A 30 and A 78 respectively (Jacoby 1979), are coextensive with the infrared dust emission. Optical spectroscopy of the central knots in A 30 by Hazard et al revealed no detectable hydrogen lines and a He/H ratio of at least 20 was derived.

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Greenstein (1981) obtained optical and ultraviolet spectrophotometry of the central star of A 30. He found that the ultraviolet extinction curve deviated from the normal interstellar extinction law, exhibiting a broad peak at 2470 Å rather than at the normal wavelength of 2200 Å. Greenstein attributed the abnormal reddening to the dust inside the nebula which is responsible for the infrared emission. The (dereddened-observed) stellar flux longwards of 912 Å is insufficient to power the observed infrared emission. Hence, direct absorption of photons below the Lyman limit by dust must occur. However, with no hydrogen in the inner nebula, it is not clear that the dust affects the ionization structure. Greenstein noted that an extinction curve for carbon smoke measured by Stephens (1980) gave a peak at the observed wavelength of 2470 Å and provided a better fit than a graphite grain model.

Iben et al (1982) have recently provided a detailed theoretical interpretation of the characteristics of the nebulosities and central stars in A 30 and A 78. According to their interpretation, the nuclei represent stars which have passed along the normal hydrogen-shell-burning central star evolutionary track, but then have experienced a final thermal pulse just after achieving a white dwarf configuration. As a result, most of the remaining hydrogen was completely burned following incorporation into the helium-burning convective shell and the stars swelled to red giant dimensions once more. The stars are now burning helium on a long timescale and retracing their path on the H-R diagram. The precise means of ejection of the inner helium-rich knots in A 30 and A 78 was not established by Iben et al, but ejection during the renewed red giant phase would provide a natural explanation for the existence of large quantities of dust in the knots.

6. INFRARED EMISSION FEATURES

Gillett, Forrest and Merrill (1973) discovered two emission features at 8.6 μm and 11.3 μm in the 8-13 μm spectra of NGC 7027 and BD+30°3639. Their initial suggestion that the 11.3 μm feature was due to $MgCO_3$ was not supported by the subsequent failure to detect other expected $MgCO_3$ features at 7 μm and 24 μm (Russell, Soifer and Willner 1977, McCarthy et al 1978). Further ground-based observations of NGC 7027 revealed an emission feature at 3.3 μm, with a weaker feature at 3.4 μm (Merrill, Soifer and Russell 1975, Grasdalen and Joyce 1976). Airborne 4-8 μm spectrophotometry of NGC 7027 by Russell, Soifer and Willner (1977) revealed two more features at 6.2 μm and 7.7 μm. The latter is the strongest of the six unidentified features. The six features have now been observed in other classes of objects besides planetary nebulae and their relative intensities have been found to vary from object to object. The 2-13 μm spectrum of HD 44179, the Red Rectangle, is shown in Figure 5 in order to illustrate the features uncontaminated by nebular emission lines. This bipolar reflection nebula, whose central star is of late B - early A spectral type, may be a planetary nebula precursor (see Cohen, these proceedings).

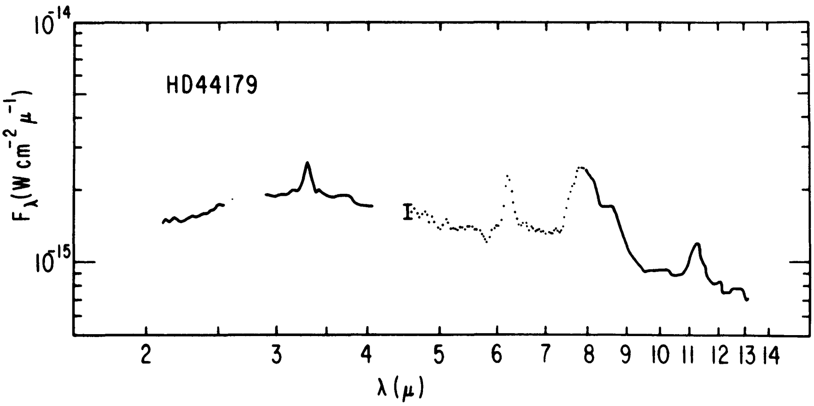

Figure 5. The 2-13 μm spectrum of HD 44179, showing the unidentified features at 3.3, 3.4, 6.2, 7.7, 8.6 and 11.3 μm (Russell et al 1978).

High spectral resolution observations of the features at 11.3 μm (Bregman and Rank 1975), 3.3 μm (Tokunaga and Young 1980) and 7.7 μm (Russell et al 1982) have shown that they are broad and not due to unresolved lines. A solid state origin is therefore implied. Although the six features are unidentified at present, an identification of at least some of them with hydrocarbons seems very probable (see below).

Spectrophotometry of the 3.3 and 3.4 μm features, in planetary nebulae other than NGC 7027, has been obtained by Russell, Soifer and Merrill (1977; IC 418 and BD+30°3639), Willner et al (1979; IC 418 and NGC 6572), Allen et al (1982; M 1-11, IC 2501, He 2-113 and CPD-56°8032) and Martin (these Proceedings). This is an insufficient sample from which to draw statistical conclusions and observations of more nebulae are needed. Similarly, 4-8 μm spectrophotometry has been published for only NGC 7027 (see above) and IC 418 (Willner et al 1979). By contrast, 8-13 μm spectrophotometry has been published for 26 different planetary nebulae: by Gillett et al (1973; 3 PN), Grasdalen (1979; 2 PN), Willner et al (1979; 2 PN), Aitken et al (1979, 1980; 5 and 2 PN) and Aitken and Roche (1982a; 20 PN). The existing sample is biased towards compact nebulae. A first step towards obtaining a less biased sample has been made by Roche, Aitken and Whitmore (these Proceedings).

Of the ten planetary nebulae so far found to show strong 11.3 μm and 8.6 μm features, five are high excitation (HeII λ4686/Hβ > 0.2), while the other five, of very low to intermediate excitation, have WC-type central stars.

Willner et al (1979) found a broad emission feature between 10.5 μm and 13 μm in the 8-13 μm spectra of IC 418 and NGC 6572. They identified the feature with SiC grains. Such grains had already been identified in the 8-13 μm spectra of many carbon stars. The SiC feature has since been seen in the 8-13 μm spectra of NGC 6790 (Aitken et al

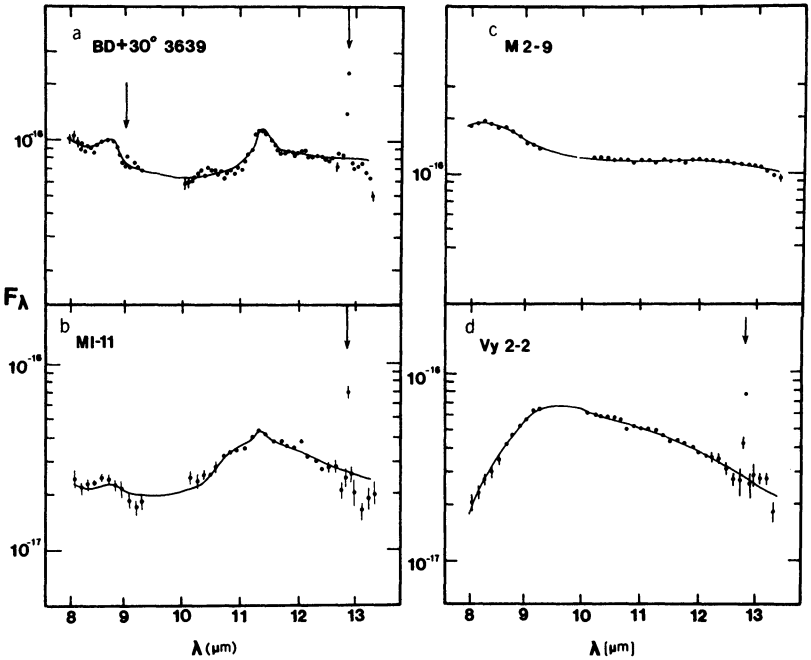

Figure 6. 8-13 μm spectrophotometry of four planetary nebulae, illustrating the various features encountered. The solid lines are best fits to the continua utilising varying proportions of featureless continuum, plus the SiC, 8.6 μm and 11.3 μm features (Figures 6a, b); and continuum plus the silicate feature in emission (6d), or in emission plus absorption (6c). Arrows indicate the positions of nebular emission lines. All figures are taken from Aitken and Roche (1982a).

1979) and IC 2501 and M 1-11 (Aitken and Roche 1982a). The 8-13 μm spectrum of M 1-11 is shown in Figure 6b, where a weak 11.3 μm feature can also be seen. The 11.3 μm feature is always weak in the spectra of planetary nebulae with strong SiC features. Conversely, Aitken and Roche (1982a) found that small amounts of the SiC component improved the fits to the spectra of planetary nebulae with strong 11.3 μm features. Unlike the 11.3 μm feature, the 3.3 μm feature shows good contrast in those planetary nebulae with strong SiC features. Three of the planetary nebulae with strong SiC features are of intermediate excitation (HeII/Hβ $\sim$ 0, [OIII]/Hβ $\sim$ 10), while IC 418 and M 1-11 have [OIII]/Hβ < 2.

Aitken et al (1979) discovered the well-known silicate feature in emission, in the 8-13 μm spectra of M 1-26, SwSt 1 and Hb 12. Since then, Aitken and Roche (1982a) have also found silicate emission in the spectra of IC 4997, He 2-47, Vy 2-2 and He 2-131. Four of this set of seven nebulae are of very low excitation ([OIII]/Hβ < 1), while Hb 12, IC 4997 and Vy 2-2 have [OIII]/Hβ $\gtrsim$ 5. Figure 6d shows the 8-13 μm spectrum of Vy 2-2.

Aitken and Roche (1982a) found that the 8-13 μm spectra of M 2-9, Mz 3, He 2-90 and M 2-56 required a combination of silicate emission with overlying absorption by colder silicate grains to fit them. The required silicate absorption optical depths implied visual extinctions $A_V \sim 15$ mag to the infrared cores, which is much larger than the interstellar extinction to these objects. These nebulae can all be loosely classified as Type I bipolar nebulae (see the reviews by Cohen and by Peimbert, these Proceedings). The 8-13 μm spectrum of M 2-9 is shown in Figure 6c.

Forrest, Houck and McCarthy (1981) found a strong emission feature in the 16-30 μm spectra of IC 418, NGC 6572 and four carbon stars. The feature extended from 24 μm to at least 30 μm. All these objects also have strong 10.5-13 μm SiC features, although some carbon stars with SiC features did not show the λ>24 μm feature. Forrest et al suggested that the grain material responsible for the feature was either Fe_3C or carbyne, the latter a long-chain allotrope of carbon which had been proposed to exist in meteorites. Recent work (e.g. Smith 1981) now suggests carbyne does not exist. Goebel (1980) proposed MgS grains.

The standard picture of dust formation in late-type stellar envelopes is that the C/O ratio determines the type of grain formed. In oxygen-rich envelopes, CO molecules should lock up all carbon atoms, leaving only oxygen-rich grains such as silicates to form, while in carbon-rich envelopes the locking up of all available oxygen atoms in CO would allow carbon-rich grains such as silicon carbide and graphite to condense. Available measurements of C/O ratios in planetary nebulae confirm this picture (Table 4, below). The nebulae with silicate emission all have C/O < 0.5 (Table 4; Flower and Penn and Cohen, Flower and Goharji, this volume). The nebulae with strong SiC emission all have C/O very close to unity and are all consistent with C/O > 1 when the small contribution from C locked up in SiC is allowed for. The nebulae with strong unidentified features all appear to have C/O > 2. The carbon abundance determinations are particularly difficult for this

TABLE 4: INFRARED EMISSION FEATURES AND NEBULAR C/O ABUNDANCE RATIOS

NEBULA	FEATURE	C/O	REFERENCE
IC 4997	silicate	0.4	see Table 1, Seaton, this volume
He 2-131	"	0.3	" " "
M 1-26	"	0.5	" " "
IC 418	SiC	1.3	" " "
NGC 6572	"	1.1	" " "
IC 2501	"	0.9	" " "
NGC 5315	11.3 μm	2.5	Torres-Peimbert and Pena (1981)
BD+30°3639	"	≥2.8	" " "
NGC 7027	"	3.5	Shields (1978)
"	"	3.2	Perinotto et al (1980)

group of nebulae. Allowance must be made for the attenuation of CIV λ1549 by internal dust in the high-excitation nebulae, while contamination of the nebular carbon lines by stellar features is a problem in those with WC type central stars. However, the evidence seems to suggest that the planetary nebulae with strong SiC features have lower C/O ratios than the planetary nebulae with strong 11.3 μm features.

The general progression, from mainly low-excitation planetaries showing silicate emission, through intermediate-excitation nebulae with strong SiC features, to high-excitation nebulae showing strong unidentified features, suggests that a correlation between initial stellar mass and C/O ratio is involved. If the high-excitation, high luminosity nebulae are identified with the more massive progenitors, this would imply that the nebulae with silicate emission have originated from the least massive progenitors. This would be consistent with the models of Renzini and Voli (1981), who predict $C/O < 1$ for low initial masses and $C/O > 1$ for higher masses. Figure 9 of Renzini and Voli also predicts that C/O can fall below unity again for the most massive progenitors ($M \geq 5\ M_\odot$), and these nebulae should also have $He/H > 0.15$. It might be possible to identify such objects with bipolar nebulae such as Mz 3 and M 2-9 which have been found to show silicate features by Aitken and Roche (1982a).

I conclude this section with a brief discussion of the origin of the unidentified emission features, along with a personal interpretation of the observations.

Allamandola and Norman (1978) proposed that the 3.3 μm and 7.7 μm features were due to C-H stretching and H-C-H bending modes of solid methane, in which the normal rotational structure of gaseous CH_4 is suppressed. Duley and Williams (1981) proposed that the features were due to radicals bound to the surface of graphite or amorphous carbon grains. They showed that such surface functional groups would give rise to spectral features characteristic of aromatic molecules. For example, an H atom bound to a carbon atom in a hexagonal graphitic platelet would correspond to an aromatic -CH complex. The identifications proposed by Duley and Williams included the CH stretch and H wag of aromatic -CH, at 3.3 μm and 11.3 μm respectively, and the asymmetric stretch of aromatic $-CH_3$, at 3.4 μm.

Barlow and Silk (1977) proposed that graphite grains would react with atomic or ionized hydrogen in the vicinity of HII regions, if their temperatures exceeded $T_d \sim 70$ K, leading to the destruction of the grains on a short timescale. Draine (1979) criticised the reaction model of Barlow and Silk on the grounds that the predicted chemical sputtering yields did not agree with low temperature laboratory data. However, Barlow (1982) has analysed all the existing experimental data and shown that H_2 recombination dominates at laboratory densities, whereas chemical sputtering will dominate at densities typical of the interstellar medium and planetary nebulae. Chemical sputtering by

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hydrogen occurs both for graphite and amorphous carbon. The analysis yielded a revised critical grain temperature, T_d(react) $\sim$ 110 K, above which chemical sputtering proceeds rapidly. The timescale for the destruction of a carbon grain of radius 10^{-6} cm was found to be $\sim 10^7/n_H$ years for a 100 K HI region and $\sim 10^6/n_H$ years for a 10^4 K HII region.

It is proposed here that surface hydrocarbon complexes formed during the chemical sputtering of carbon grains are responsible for the observed infrared emission features. The main product of chemical sputtering is the abstraction of a carbon atom to yield CH_4. Excitation of the CH_4 on the surface could give the 3.3 µm and 7.7 µm features. The steps along the path to the creation of CH_4 give -CH, -CH_2 and -CH_3. These aromatic complexes could give the 3.3 µm and 11.3 µm features, as discussed by Duley and Williams. C_2H_4 and similar hydrocarbons are also formed during the chemical sputtering of graphite and could be responsible for the other features.

The observations of the spatial distribution of the infrared features in NGC 7027 are consistent with this model. Jones et al (1980) found that the 7.7, 8.6 and 11.3 µm features showed greatest contrast in the outer regions. The high spatial resolution observations of Aitken and Roche (1982b) confirm this and show conclusively that the 11.3 µm feature originates from a shell outside the ionized zone (see Section 4 and Figure 4). Although molecular H_2 in a neutral zone will not react with graphite, a dissociation front will propagate ahead of the advancing ionization front, yielding H atoms which can then react rapidly with the grains.

Two excitation mechanisms have been suggested for the infrared features. Allamandola and Norman (1978) proposed excitation by ultra-violet fluorescence, in which absorption of short wavelength photons by surface molecules leads to the excitation of vibrational transitions. Aitken and Roche (1982b) have calculated the implied fluorescence yields in NGC 7027 for this mechanism. The observed flux of photons in the infrared features is 2.9×10^4 cm^{-2} s^{-1}. The available flux of nebular photons between 1200 and 5007 Å is 2.8×10^4 cm^{-2} s^{-1} (see Table 2), implying a yield of unity if this mechanism operates. We thus have the remarkable situation that the number and luminosity of nebular photons between 1200 and 5007 Å is equal to the number of infrared feature photons and the continuum infrared luminosity, respectively.

An alternative to UV fluorescence, namely thermal excitation has been suggested by Dwek et al (1980), who propose that the emitting material is thermally excited on warm grains. The most severe constraint on this model is provided by the 3.3 µm feature, which requires significantly hotter grain temperatures for excitation than the other features. However, it is interesting that the brightness temperature for the 3.3 µm feature in NGC 7027, quoted by Aitken and Roche (1982b), is equal to the temperature of the $\lambda^{-2}B_\lambda$(230 K) continuum which seems to originate from the ionized zone (Section 4). A comparison of the spatial distribution of the 3.3 µm and 11.3 µm features in NGC 7027 could be very useful.

The association of the infrared features with carbon-rich planetary nebulae can be understood if they originate from carbon grains. Objects with C/O ratios only slightly larger than unity will have most of their excess carbon locked up in SiC grains which condense before graphite grains. This would explain the weakness of the 11.3 μm feature in planetary nebulae with the SiC feature and C/O $\sim$ 1. For C/O > 2, SiC grains will not use up a significant fraction of the excess carbon, allowing large quantities of carbon grains to form. This would be followed by the production of strong infrared features when the grains are destroyed.

The progressive destruction of carbon grains in the envelopes of carbon-rich planetary nebulae would explain the decrease of the dust-to-gas ratio with increasing nebular age, which was found by Natta and Panagia (1981). The confinement of carbon grains to the neutral shells and ionization fronts of optically thick planetary nebulae would be consistent with the depleted dust-to-gas ratios found in the ionized zones of both optically thick and thin planetary nebulae (Section 3.4). The anomalously large quantities of dust in the inner regions of A 30 and A 78, along with the carbon composition of the dust in A 30, suggested by its extinction curve (Section 5), also find an explanation. Since no hydrogen exists in the inner regions of these nebulae, carbon grains formed during the revisited red giant phase would not have been destroyed.

Silicate grains in oxygen-rich planetary nebulae will not be destroyed chemically and so there should be no decrease of the dust-to-gas ratio in such nebulae with increasing age. Although carbon grains can be destroyed in planetary nebulae envelopes, this does not necessarily imply that carbon-rich progenitor stars do not enrich the interstellar medium carbon grain content. The differences between derived progenitor star masses and current central star masses are often much larger than the mass of the planetary nebula envelopes (see the reviews by Renzini and by Schönberner and Weidemann in this volume). Most of the missing mass may have been lost as a late-type stellar wind prior to PN envelope ejection. Carbon grains in these winds will not react with the ambient H_2 during the carbon star phase and will be too distant to be heated sufficiently for reaction with atomic or ionized hydrogen during the planetary nebula phase. Thus, providing planetary nebulae envelopes represent a small fraction of the total mass lost, carbon star progenitors can enrich the grain content of the interstellar medium.

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KWOK: Would you comment on the difference between grains in novae and in PN?

BARLOW: Most novae showing dust emission appear to have featureless infrared continua, although recently Aitken and Roche have discovered a 10 μm "silicate" emission feature in the spectrum of Nova Aquilae 1982.

KALER: Feibelman and I are completing a study of A 78. We can fit the IUE spectrum to a model or a black-body at 90 000 - 100 000 K, and there is little evidence for dust surrounding the star. Given the strong infrared emission, we conclude that the dust must be distributed in such a way that the starlight is not absorbed.

BARLOW: This is very interesting. We at UCL have also acquired IUE spectra of A 30 and A 78 in view of the great importance of Greenstein's discovery of anomalous extinction towards A 30.

HOUCK: The failure of the search for the 25 μm feature of carbonates may be due either to radiative transfer or crystallographic effects. Carbynes seem not to exist in meteorites but I think that the chemists still believe in them.

BARLOW: Although the existence of carbynes is theoretically possible, as I understand it there is no definitive laboratory evidence for their existence.

ZUCKERMAN: To determine the total mass of dust associated with a PN, it is best to observe at submillimeter wavelengths where the intensity of emission is only weakly dependent on the dust temperature. A group of astronomers (Jaffe and Hildebrand, Chicago; Gatley, UKIRT; Roellig and Werner, NASA-Ames; Sopka and myself, Maryland) has used ^{3}He bolometers on UKIRT to measure 380 μm fluxes from infrared giant stars and PN. We have observed about a dozen such objects and found that, along with IRC + 10216 and OH 0739 - 14, the planetary and proto-planetary nebulae NGC 7027, GL 2688 and GL 618 are strong 380 μm sources. There is clearly a large amount of cool dust around these objects since, for example, GL 2688 is as bright as IRC + 10216 at 380 μm, whereas the latter is at least 100 times more intense at much shorter wavelengths (e.g. 5 μm).

ALLER: To what extent can we be sure that the carbon particles are classical graphite structures? Do we have any theoretical or experimental data which enable us to predict detailed structures of microscopic particles?

BARLOW: Laboratory samples of amorphous carbon tend to be composed of random ensembles of graphite microcrystals. Whether 10^{-6} cm radius carbon particles will be graphite structured or truly random collections of carbon atoms is hard to predict, but, until laboratory data are available on truly amorphous carbon particles, I suspect that graphite data will tend to be used.

ZUCKERMAN: About ten years ago, the Caltech infrared group published some beautiful maps of NGC 7027 which showed that the infrared emission at, say, 10 μm came from the same region as the radio emission. Are you now saying that this infrared radiation is not emitted by dust grains located within the ionized gas?

BARLOW: No. The reduced intensity of the C IV resonance lines in the ultraviolet spectrum of NGC 7027 shows that dust is present in the ionized gas. This dust will presumably be the hottest dust and emit much more strongly at 10 μm than the cool (95 K) dust supposed to exist in the surrounding neutral shell.