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DUST IN PLANETARY NEBULAE

SUN KWOK
Herzberg Institute of Astrophysics, National Research Council of Canada
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ABSTRACT

A two-component dust model is suggested to explain the infrared emission from planetary nebulae. A cold dust component located in the extensive remnant of the red-giant envelope exterior to the visible nebula is responsible for the far-infrared emission. A warm dust component, which is condensed after the formation of the planetary nebula and confined within the ionized gas shell, emits most of the near- and mid-infrared radiation. The observations of NGC 7027 are shown to be consistent with such a model. The correlation of silicate emission in several planetary nebulae with an approximately +1 spectral index at low radio frequencies suggests that both the silicate and radio emissions originate from the remnant of the circumstellar envelope of the precursor star and are observable only while the planetary nebula is young. It is argued that oxygen-rich stars as well as carbon-rich stars can be progenitors of planetary nebulae.

Subject headings: interstellar: matter — nebulae: planetary — stars: evolution.

I. INTRODUCTION

Since the discovery of strong infrared excess in planetary nebulae (Gillett, Low, and Stein 1967), the infrared spectra have remained one of the most perplexing problems of planetary nebulae. It is now widely accepted that dust grains are responsible for infrared emission. However, the chemical composition and the spatial distribution of the grains are not clear (Balick 1978; Mathis 1978). The best-studied nebula, NGC 7027, has a significant amount of far-infrared radiation which must be emitted by dust grains of temperatures much lower than those implied by the near- and mid-infrared measurements (Telesco and Harper 1977). This result has been confirmed by means of medium-resolution spectroscopy in the 16–38 μm region by McCarthy, Forrest, and Houck (1978). Observations of several other planetaries at 35 and 75 μm also show similar dual-component structure in the infrared spectra (Moseley and Harper 1978).

The far-infrared spectrum of NGC 7027 has been fitted, by both Telesco and Harper (1977) and McCarthy, Forrest, and Houck (1978), with thermal emission from dust grains at a temperature of approximately 90 K. The grain emissivity (Q_λ) is assumed to have a wavelength dependence of the form λ^{-2}, which is appropriate for small graphite grains. This implies that the dust grains are confined to a relatively thin shell, as the dust temperature is expected to vary with distance from the central heating source if the dust grains are distributed over an extended region.

The most common interpretation of the thin-shell model is that the dust grains are formed during the expansion of the suddenly ejected gas shell (Gillet, Merrill, and Stein, 1972; Hunter 1973). The pros and cons of this model have been discussed by Scalo and Shields (1979). It is also clear that a thin-shell model cannot account for the existence of two color temperatures in the infrared spectrum (in the case of NGC 7027, one at 90 K and the other at 200–300 K). An ad hoc explanation may be offered by introducing two chemically different grains or two vastly different grain sizes coexisting in a thin shell. However, it would be much more desirable to relate the two dust components to other well-observed grain-formation processes. In this paper we shall develop a more coherent picture of dust in planetary nebulae and discuss its implications for the origin and evolution of planetary nebulae.

II. SPATIAL DISTRIBUTION OF DUST IN NGC 7027

Evidence already exists for the presence of a neutral envelope exterior to the optical nebula (~10″ in size) of NGC 7027. CO emission is detected from a region 30″ × 60″ in size (Mufson, Lyon, and Marionni 1975) and faint Hβ and Hα halos have been seen to extend over areas of 25″ × 22″ and 50″ × 40″, respectively (Coleman, Reay, and Worswick 1975; Atherton *et al.* 1979). Recent narrow-band interference-filter observations of NGC 7027 using a Reticon array also show an extended image size of ~35″ (A. Condal, private communication). Since dust is undoubtedly associated with this extended envelope, its existence has to be taken into account in any discussion of the infrared spectrum. Red giants, which are widely believed to be progenitors of planetary nebulae, are known to have undergone extensive mass loss while on the asymptotic branch. The remnant of the circumstellar envelope formed by such mass-loss processes may still be observable in the planetary-nebula phase, and the CO envelope of NGC 7027 may be identified with such a remnant. If this is the case, then dust in the remnant circumstellar envelope will be expected to be radiating in the far-infrared and could be responsible for the long-wavelength emission from NGC 7027.

Dust grains have also been seen to be condensing in the high-velocity wind from the nuclei of two planetary nebulae (Cohen and Barlow 1974; Cohen *et al.* 1977). Since these grains are condensed after the formation of the nebulae, they are likely to have a chemical composition different from the cold component; for example, grains condensed in an ionized environment (e.g., around novae and Wolf-Rayet stars) seem to be different from those condensed in the outer atmospheres of late-type stars (Ney and Hatfield 1978; Cohen, Barlow, and Kuhi 1975; Williams *et al.* 1978; Merrill 1977). Because of the high velocities of winds generated by planetary-nebula nuclei, these "new" grains will aggregate in the gas shell and can be characterized by a single dust temperature. This component will dominate the emission in the near- and mid-infrared and is possibly responsible for the 200–300 K component in the spectrum of NGC 7027.

Let us first consider the far-infrared component. The emitting region can safely be assumed to be optically thin for infrared emission beyond 20 μm. In the general case of an extended shell with inner and outer radii r_0 and R, the infrared flux received by the telescope beam can be written as

$$F_\lambda = \frac{1}{D^2}\int^{\text{beam}} 2\pi p dp \times \int_{R'}^{\surd(R^2-p^2)} 2\pi a^2 Q_\lambda(a) B_\lambda(T_d) n_d dl\,, \qquad (1)$$

where p is the projected distance from the center of the nebula, $R' = 0$ if $p > r_0$, $R' = (r_0{}^2 - p^2)^{1/2}$, if $p > r_0$, D is the distance to the nebula, a the radius of the grain, Q_λ the emission/absorption efficiency of the grain, B_λ the Planck function, T_d the dust temperature, n_d the number density of the grains, and dl the length element along the line of sight. Assuming that the grains are perfect absorbers of the heating radiation and that Q_λ has a power-law wavelength dependence in the far-infrared ($Q_\lambda \propto \lambda^{-\alpha}$, $\alpha > 0$), T_d can be expressed as $T_d = T_0(r_0/r)^\beta$, where $\beta = 2/(4 + \alpha)$. If the density distribution is also assumed to have a power-law dependence on distance from the center of the nebula ($n_d \propto r^{-n}$), then the infrared spectrum is mostly determined by the two parameters α and n. It can easily be seen that a uniform density over an extended volume is incompatible with the observations, since the outer (and cooler) grains will dominate the far-infrared emission and the spectrum will be broader than observed. A density gradient ($n > 0$) is clearly necessary in the extended-shell model.

Both theoretical (Kwok 1975) and observational studies (Kuiper *et al.* 1976; McMillan and Tapia 1978) of the structure of circumstellar envelopes of late-type stars show that the gas and dust density profiles can be adequately described by an inverse-square power law. If the CO envelope of NGC 7027 is the result of a steady stellar wind in the red-giant phase, the density distribution of the grains is

$$n_d = \left(\frac{3Ayfg}{16\pi^2 a^3 \rho_s \mu}\right)\left(\frac{\dot{M}}{V_d}\right)\frac{1}{r^2} \equiv \frac{B^2}{r^2}\,, \qquad (2)$$

where A is the molecular weight of the grain material, y the relative number abundance of the grain material, f the fraction of the grain material which has condensed into grains, g the enrichment factor, ρ_s the density of the grains, $\dot{M}$ the mass-loss rate during the red-giant phase, and V_d the grain ejection velocity. Substituting equation (2) into equation (1), the flux due to the cold component can be readily obtained:

$$F_\lambda = \frac{2\pi a^2 B}{D^2} Q_\lambda(a) \frac{2hc^2}{\lambda^5}\int^{\text{beam}} 2\pi p dp \times \int_{\max(p,r_0)}^{R} \frac{dr}{r(r^2-p^2)^{1/2}\{\exp[(h\nu/kT_0)(r/r_0)^\beta] - 1\}}\,. \qquad (3)$$

We have fitted the infrared spectrum of NGC 7027 between 1 and 40 μm with a two-component model (Fig. 1). The data between 1 and 14 μm are taken from Russell, Soifer, and Willner (1977) and the rest from McCarthy, Forrest, and Houck (1978). Since the chemical composition of the hot component is uncertain, we do not attempt to reproduce the grain features, but instead fit the continuum by a $\lambda^{-2}B_\lambda$(230 K) law. The cold dust grains are assumed to be graphite of size 1 μm. The absorption/emission cross sections are calculated following the work of Gilman (1974). For graphite grains of size ~ 1 μm, α has a value between 1 and 1.5 in the far-infrared domain, and a value of 1.25 (implying a value of 0.38 for β) is adopted in this calculation. This is consistent with the value estimated by Campbell *et al.* (1976) for the dust in the circumstellar envelope of IRC +10°216. In order to reproduce the absolute level of the observed flux, a value of $\dot{M}/V_d = 1.8 \times 10^{-6}(M_\odot\ \text{yr}^{-1})/(\text{km s}^{-1})$ is required, assuming normal abundance of carbon ($y = 3.3 \times 10^{-4}$, Allen 1973) and a distance to NGC 7027 of 1 kpc.

From Figure 1 we can see that radiation from the cold component is dominant beyond 30 μm, and it would seem that the angular extent of this component could be measured by determining the brightness distribution at long wavelengths. Relative 53 μm flux densities at four positions along the long axis of NGC 7027 have in fact been obtained by Telesco and Harper, and they concluded that the source is no larger than 25″ in size. We have compared their observations with the result of a convolution of the predicted 53 μm emission from the remnant of the red-giant envelope, described above, with a 28″ beam (as used by Telesco and Harper). The observations are found to be consistent with an envelope of radius as large as 100″ (Fig. 2). Similar convolutions with a 2″.5 beam are shown in Figure 3 together with the 20 μm scan by Becklin, Neugebauer, and Wynn-Williams (1973). We can see that the simulated scan agrees very well with the observations, both in shape and angular extent. The observed angular size is slightly smaller, probably because of contamination by emission from the new grains in the shell. These two comparisons show that

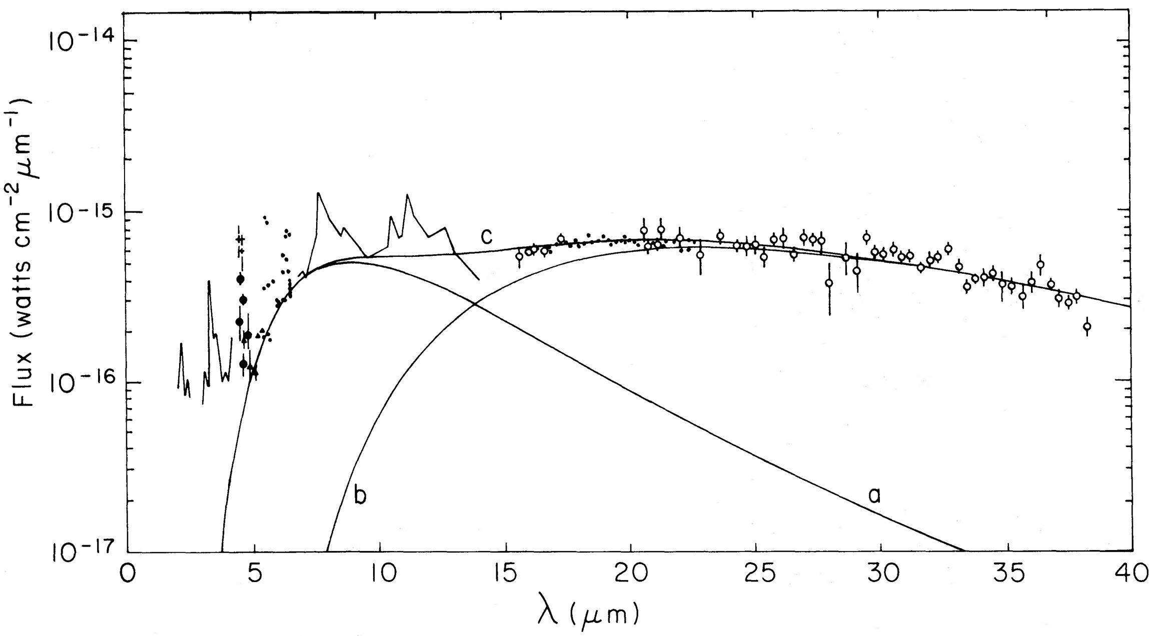

FIG. 1.—The spectrum of NGC 7027 from 1 to 40 μm, fitted by the two-component dust model. The data are from Russell, Soifer, and Willner (1977) and McCarthy, Forrest, and Houck (1978). The warm component (*curve a*) is calculated from $\lambda^{-2}B_\lambda(230\text{ K})$ and the cold component (curve *b*) from eq. (3). Curve *c* is the sum of curves *a* and *b*. The inner and outer radii of the cold component are 5″ and 80″, respectively. Dust temperature at the inner radius is 125 K. The beam size used is 32″. Other parameters are described in the text. The predicted flux (F_ν) at 131 μm is 99 Jy, comparable to the wide-band (Δ_λ = 128 μm) upper limit (2 σ) of 76 Jy obtained by Telesco and Harper (1977).

the brightness distribution is not a reliable way of determining the physical extent of the emission region.

Such a seemingly peculiar result can be understood by the following analysis. For an extended, optically thin dust shell, with density and temperature gradient, the total flux radiated within radius R is given by

$$F_\lambda = \frac{1}{D^2}\int_{r_0}^{R} 4\pi r^2 n_d(r) Q_\lambda B_\lambda(T_d)dr$$

$$\propto \int_{y_0}^{y_1} \frac{y^{(3-n-\beta)/\beta}}{[\exp(y)] - 1}\,, \tag{4}$$

where $y_0 = hc/\lambda k T_0$, $y_1 = y_0(R/r_0)^\beta$ and $y = y_0(r/r_0)^\beta$. We have plotted the above integral as a function of R/r_0 in Figures 4*a*, 4*b*, and 4*c*, illustrating the effects of temperature and density gradients. While the difference between $\beta = 0.38$ and $\beta = 0.33$ cases (corresponding to $\alpha = 1.25$ and $\alpha = 2$, respectively) is small, the $n = 0$, 1, and 2 cases are clearly distinct from each other. In the $n = 2$ case, most of the flux is emitted from the central region of the cloud with only weak dependence on the extent of the cloud (R). This effect is more pronounced at shorter wavelengths (as can be seen by comparing Figs. 4*a*, 4*b*, and 4*c*) where the outer and colder grains contribute very little. Only at wavelengths long enough to be on the Rayleigh-Jeans part of the spectrum for all emitting dust grains could we see the flux dependence on R. Using any reasonable choice of T_0, the remnant of a stellar wind outside the visible shell of a planetary nebula will appear to give a small angular size at mid-infrared wavelengths. CO line emission, being optically thick, gives a better indication of the true size of the source.

One may think that an extended emission region will lead to changes in received flux when the nebula is observed with different telescope-beam sizes. Table 1 shows the expected variations in F_λ at several wavelengths for the same emission region (the cold com-

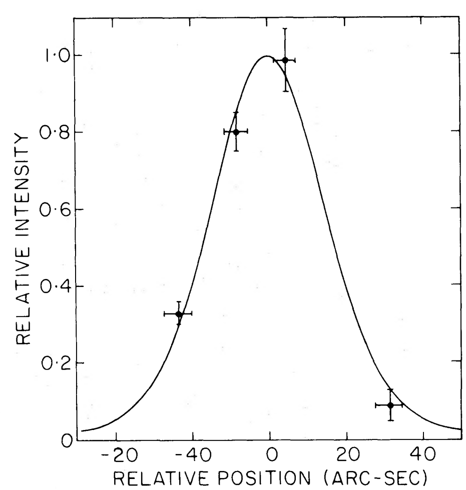

FIG. 2.—Beam convoluted relative 53 μm flux densities as a function of angular displacement from the center of the nebula. Parameters are described in Fig. 1 and the text. The beam diameter (FWHM) is 28″. The data points are relative flux densities obtained by Telesco and Harper (1977) at four positions along the long axis of NGC 7027.

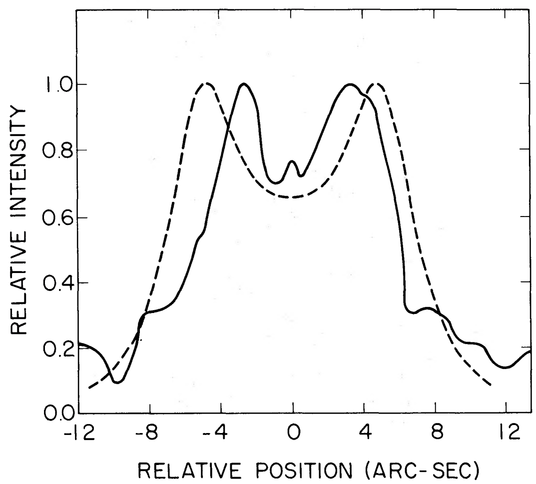

FIG. 3.—Right-ascension scan at 20 μm by Becklin, Neugebauer, and Wynn-Williams (*solid line*) compared to a simulated scan (*dotted line*) across the remnant red-giant envelope outside the optical nebula. Parameters of the envelope are described in Fig. 1 and the text. The beam size is 2.5″.

ponent) discussed in Figures 1, 2, and 3. The amount of mid-infrared flux received is not very sensitive to increases of beam size beyond 20″. Only at very long wavelengths is the aperture dependence easily observable.

To compare with observations, we have from the literature flux values (F_ν) of 1103 ± 130 Jy at 33 μm (beam width 13″, Dyck and Simon 1976) and 1509 ± 350 Jy at 36 μm (beam width 50″, Telesco and Harper 1977). The predicted flux ratio from the model is 0.55, which is not grossly at variance with the observed ratio. Another multi-aperture observation (at 53 μm) is given by Telesco and Harper, who reported 759 Jy and 814 Jy for 28″ and 50″ apertures, respectively; the error (including uncertainties in calibration and data reduction) is ~160 Jy. The ratio predicted by the model is 0.76, certainly within the error margins. We should note that the present model is based on a very simple geometry. In reality, when the gas shell collides with the remnant wind, diffusion of matter will occur at the interaction point, causing the density distribution to deviate from the "δ-function + $1/r^2$ law" pictured in this model. Most likely a steeper density gradient will result, in the region just outside the shell, and this will lead to a further decrease in the apparent angular size of the source. A more accurate determination of the far-infrared flux dependence on aperture may provide a better estimate of the physical extent of the emission region outside the visible nebula.

It is difficult to imagine that the CO envelope around NGC 7027 would emit no infrared radiation, for molecules are always embedded in dust clouds. The identification of the CO envelope with the remnant of the red-giant wind resolves the problem of the small apparent angular size of the infrared emitting region.

While we do not contend that the parameters derived here give an exact description of NGC 7027 (e.g., we

TABLE 1

RELATIVE FLUX DENSITY[a] AS A FUNCTION OF BEAM SIZE

BEAM SIZE (arcsec)	F_λ 20 μm	25 μm	30 μm	40 μm	61 μm	131 μm
50.....	1.04	1.08	1.12	1.19	1.30	1.44
30.....	1	1	1	1	1	1
20.....	0.89	0.85	0.82	0.78	0.73	0.68
10.....	0.37	0.33	0.31	0.27	0.24	0.21
5.....	0.07	0.07	0.06	0.06	0.05	0.05

[a] Normalized with respect to the 30″ beam size.

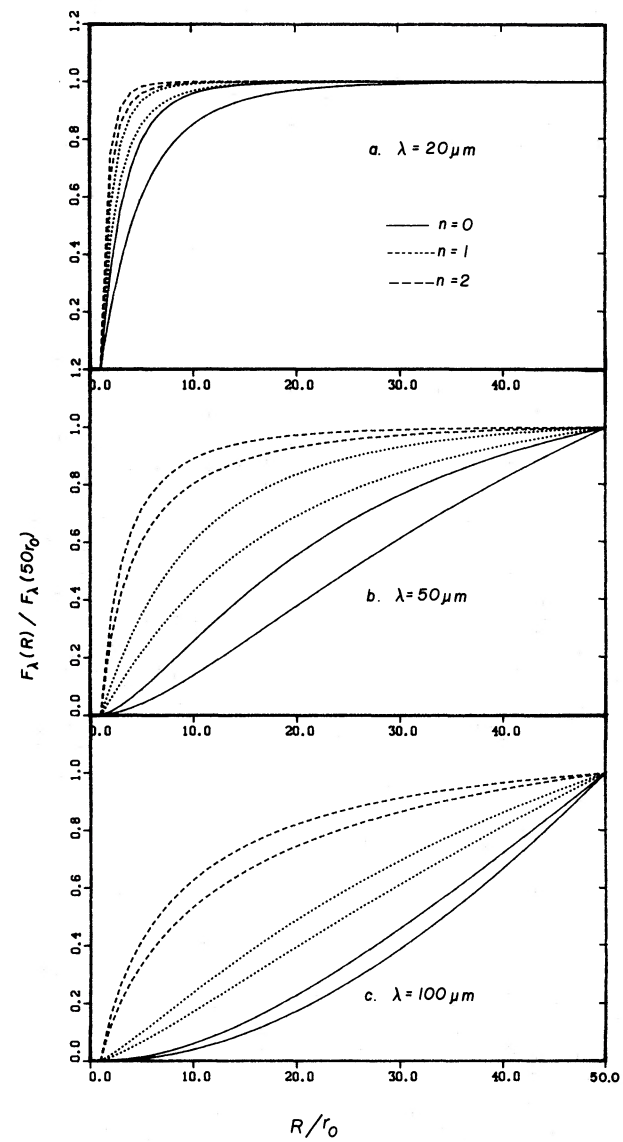

FIG. 4.—Relative flux density as a function of cloud size at 20, 50, and 100 μm. Each graph shows the effects of density gradient (n) and temperature gradient (β) on the flux dependence on R. The upper curve of each pair is for $\beta = 0.38$ and the lower curve $\beta = 0.33$. T_0 is chosen to be 125 K.

have assumed a spherically symmetric nebula, which is obviously too stimplistic), we hope we have illustrated the point that the brightness distribution observed is dependent on the density structure of the source. The conclusions drawn here for NGC 7027 may also be useful in the interpretation of the observations of other celestial objects.

III. CHEMICAL COMPOSITION OF DUST GRAINS IN PLANETARY NEBULAE

Several materials have been suggested to be responsible for infrared emission in planetary nebulae. Carbonates and sulfates were first proposed by Gillett, Forrest, and Merrill (1973) and later by Bregman and Rank (1975) to explain the 11.3 μm feature in NGC 7027. Deficiency of iron in the gas phase in six planetaries has also been used as evidence for iron condensation into grains (Shields 1975, 1978). Graphite has always been a favorite candidate because of its high abundance and the lack of infrared features. The 10 μm silicate feature, while commonly seen in oxygen-rich late-type stars, has, for a long time, not been detected in planetary nebulae. Its absence, together with the apparent overabundance of carbon in the gas phase (Shields 1978; Panagia, Bussoletti, and Blanco 1977) and the detection of CO in planetary nebulae, has led to the suggestion that carbon stars are progenitors of planetary nebulae with masses $\geqslant 0.1\ M_{\odot}$ (Zuckerman *et al.* 1976, 1978). It is unlikely, however, that all planetary nebulae evolved from carbon stars.

If some of the progenitors of planetary nebulae are oxygen-rich, then why is the silicate feature not observed in either absorption or emission? This can be explained by the properties of the inverse-square density distribution. For a stellar wind that originates from a base of radius R_{in}, the optical depth toward the center is $\pi a^2 QB/R_{\text{in}}$. Under optically thin conditions, the prominence of the silicate feature is directly proportional to its optical thickness. In the case of the circumstellar envelopes of late-type stars, R_{in} is of the order of the stellar radius; and assuming a modest mass-loss rate, the optical thickness at 10 μm can be quite appreciable and the silicate feature easily observable. However, for the remnant of a red-giant wind outside a planetary-nebula gas shell, R_{in} is $\sim 10^4$ larger than the radius of the red giant itself, and we should not expect to see the silicate signature, either in emission or in absorption against the continuum provided by the later-emerged warm dust component.

The condition of $\tau_{\text{silicates}} \ll 1$ may not hold for young planetary nebulae where R_{in} is small. Silicate features are indeed seen in two candidates for very young planetary nebulae. V1016 Cygni and HM Sge, which used to be red stars, have both brightened recently and now have emission-line spectra similar to that of a planetary nebula (see, e.g., Ciatti, Mammano, and Vittone 1978). Their radio and infrared spectra are both distinct from those of normal planetary nebulae. Their radio continua have a spectral index of $\sim +1$, which is characteristic of free-free emission from a stellar wind. Their infrared spectra are consistent with a ~ 1000 K blackbody with a 10 μm silicate feature superposed (Davidson, Humphreys, and Merrill 1978; Puetter *et al.* 1978). It has been suggested that the hot blackbody is due to dust grains newly formed after the brightening and that the silicate grains are remnants of the precursor star (Kwok and Purton 1979; Kwok 1977). As the remnant of the circumstellar envelope is continuously being swept up by the shell, the temperature of the silicate grains will decrease. When the dust temperature falls below ~ 150 K, the 10 μm and 20 μm features will fall on the exponential side of the blackbody curve and become invisible. The near-infrared spectrum will then be dominated by emission from new grains. For an evolved planetary nebula it becomes impossible to determine whether it has an oxygen- or carbon-rich progenitor from its infrared spectrum.

Recently, 10 μm silicate features have also been detected in three other planetary nebulae (HB 12, M1-26, SwSt 1, Aitken *et al.* 1979). It is interesting to note that these are all compact (and possibly young) nebulae; and among the three, two (HB 12 and SwSt 1 = HD 167362) have a spectral index of $\sim +1$ in the optically thick region of the radio continuum, similar to that of V1016 Cygni and HM Sge (Marsh, Purton, and Feldman 1976). This implies the presence of a stellar wind and can be understood in the following picture of planetary-nebula evolution. During the early stages of the development of a planetary nebula, radio emission from the shell is limited by its angular size, and the radio continuum of the nebula may be dominated by emission from the more extended remnant of the red-giant wind. As the shell expands, the relative contribution to the radio flux will gradually shift from the wind to the shell and eventually the radio spectrum will revert to the familiar thermal spectrum similar to that of NGC 7027. If this description of the evolutionary process is correct, then an accurate determination of the spectral index in the low-frequency region and the detection of the silicate feature may serve as useful criteria for the age of the nebula. The three planetary nebulae observed by Aitken *et al.* are therefore probably of relatively young age. This conclusion is supported by the low-excitation nature of these objects (Sanduleak and Stephenson 1972), which may be due to the quenching of forbidden lines in the newly formed dense shell.

IV. CONCLUSIONS

We have explored the possibility of an extended dust-shell model for NGC 7027 with the following conclusions:

1. A significant amount of cold dust can be present outside the optical nebula without contradicting the observational data presently available. It is possible that the far-infrared radiation is emitted from dust grains associated with the extended CO envelope, which is the remnant of the stellar wind from the precursor star.

2. More generally, we suggest the existence of two

dust components in planetary nebulae. A cold component which emits predominantly in the far-infrared is located in the remnant of the red-giant wind. A warm component which is responsible for emission in the near- and mid-infrared, is confined within the optical nebula and probably is formed after the formation of the nebula.

3. The 10 μm silicate feature is seen in several candidates for young planetary nebulae. This is consistent with the suggestions that silicate grains may be condensed and ejected during the preceding red-giant phase and that oxygen-rich stars, as well as carbon-rich stars, can be progenitors of planetary nebulae.

Observations both in the radio and infrared indicate that the spectra of a young planetary nebula are likely to be different from those of an evolved one. Theories on the formation of planetary nebulae would be best tested by the identification and observation of very young planetary nebulae.

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REFERENCES

Aitken, D. K., Roche, P. F., Spenser, P. M., and Jones, B. 1979, preprint.
Allen, C. W. 1973, *Astrophysical Quantities* (3d ed.; London: Athlone), p. 102.
Atherton, P. D., Hicks, T. R., Reay, N. K., Robinson, G. J., and Worswick, S. P. 1979, *Ap. J.*, **232**, 786.
Balick, B. 1978, in *IAU Symposium 76, Planetary Nebulae Observations and Theory*, ed. Y. Terzian (Dordrecht: Reidel), p. 275.
Becklin, E. E., Neugebauer, G., and Wynn-Williams, C. G. 1973, *Ap. Letters*, **15**, 87.
Bregman, J. D., and Rank, D. M. 1975, *Ap. J.* (*Letters*), **195**, L125.
Campbell, M. F., *et al.* 1976, *Ap. J.*, **208**, 396.
Ciatti, F., Mammano, A., and Vittone, A. 1978, *Astr. Ap.*, **68**, 251.
Cohen, M., and Barlow, J. J. 1974, *Ap. J.*, **193**, 401.
Cohen, M., Barlow, M. J., and Kuhi, L. V. 1975, *Astr. Ap.*, **40**, 291.
Cohen, M., Hudson, H. S., O'Dell, S. L., and Stein, W. A. 1977, *M.N.R.A.S.*, **181**, 233.
Coleman, C. I., Reay, N. K., and Worswick, S. P. 1975, *M.N.R.A.S.*, **171**, 239.
Davidson, K., Humphreys, R. M., and Merrill, K. M. 1978, *Ap. J.*, **220**, 239.
Dyck, H. M., and Simon, T. 1976, *Pub. A.S.P.*, **88**, 738.
Gillett, F. C., Forrest, W. J., and Merrill, K. M. 1973, *Ap. J.*, **183**, 87.
Gillett, F. C., Low, F. J., and Stein, W. A. 1967, *Ap. J.* (*Letters*), **149**, L97.
Gillett, F. C., Merrill, K. M., and Stein, W. A. 1972, *Ap. J.*, **772**, 367.
Gilman, R. C. 1974, *Ap. J. Suppl.*, **28**, 397.
Hunter, J. H., Jr. 1973, *Ap. J.*, **180**, 99.
Kuiper, T. B. H., Knapp, G. R., Knapp, S. L., and Brown, R. L. 1976, *Ap. J.*, **204**, 408.
Kwok, S. 1975, *Ap. J.*, **198**, 583.
———. 1977, *Ap. J.*, **214**, 437.
Kwok, S., and Purton, C. R. 1979, *Ap. J.*, **229**, 187.
Marsh, K. A., Purton, C. R., and Feldman, P. A. 1976, *Astr. Ap.*, **49**, 211.
Mathis, J. S. 1978, in *IAU Symposium 76, Planetary Nebulae Observations and Theory*, ed. Y. Terzian (Dordrecht: Reidel), p. 281.
McCarthy, J. F., Forrest, W. J., and Houck, J. R. 1978, *Ap. J.*, **224**, 109.
McMillan, R. S., and Tapia, S. 1978, *Ap. J.* (*Letters*), **226**, L87.
Merrill, K. M. 1977, in *IAU Colloquium 42, The Interaction of Variable Stars with their Environment*, ed. R. Kippenhahn, J. Rahe, and W. Strohmeier (Bamberg: Astronomisches Institut), p. 446.
Moseley, H., and Harper, D. A. 1978, in *IAU Symposium 76, Planetary Nebulae Observations and Theory*, ed. Y. Terzian (Dordrecht: Reidel), p. 124.
Mufson, S. L., Lyon, J., and Marionni, P. A. 1975, *Ap. J.* (*Letters*), **201**, L85.
Ney, E. P., and Hatfield, B. F. 1978, *Ap. J.* (*Letters*), **219**, L111.
Panagia, N., Bussoletti, E., and Blanco, A. 1977, in *CNO Isotopes in Astrophysics*, ed. J. Andouze (Dordrecht: Reidel), p. 45.
Puetter, R. C., Russell, R. W., Soifer, B. T., and Willer, S. P. 1978, *Ap. J.* (*Letters*), **223**, L93.
Russell, R. W., Soifer, B. T., and Willner, S. P. 1977, *Ap. J.* (*Letters*), **217**, L149.
Sanduleak, N., and Stephenson, C. B. 1972, *Ap. J.*, **178**, 183.
Scalo, J. M., and Shields, G. A. 1979, *Ap. J.*, **228**, 821.
Shields, G. A. 1975, *Ap. J.*, **195**, 475.
———. 1978, *Ap. J.*, **219**, 559.
Telesco, C. M., and Harper, D. A. 1977, *Ap. J.*, **211**, 475.
Williams, P. M., Beattie, D. H., Lee, T. J., Stewart, J. M., and Antonopoulou, E. 1978, *M.N.R.A.S.*, **185**, 467.
Zuckerman, B., Gilra, D. P., Turner, B. E., Morris, M., and Palmer, P. 1976, *Ap. J.* (*Letters*), **205**, L15.
Zuckerman, B., Palmer, P., Gilra, D. P., Turner, B. E., and Morris, M. 1978, *Ap. J.* (*Letters*), **220**, L53.

S. Kwok: Herzberg Institute of Astrophysics, National Research Council Canada, 100 Sussex Dr., Ottawa, Ontario K1A 0R6, Canada