DUST IN PLANETARY NEBULAE

John S. Mathis
University of Wisconsin-Madison

In this review I shall concentrate on theoretical aspects of dust in planetary nebulae (PN), since Dr. Balick has reviewed observations in the preceding paper. I shall consider the questions, how much dust is there in PN? What is its composition? What effects does it have on the ionization structure? On the dynamics of the nebula?

HOW MUCH DUST IS THERE IN PN?

The absorption within NGC 7027 has been detected in two ways. Hicks et al.(1976) interpreted the ratio of the red- and blue-displaced components of [O III] λ5007 as indicating an absorption optical depth of about 0.3. Bohlin et al. (1975) found a depletion of C IV λ1550 relative to [C III] λ1909. This depletion probably arises from absorption on the long path encountered by λ1550, a resonance line, in escaping. An absorption optical depth of about 0.2 along a radius is indicated, which does not conflict with 0.3 for the optical depth at λ5007; the λ1550 is scattered resonantly within the volume in which C is triply ionized, while the dust absorbing red-shifted λ5007 can be anywhere within the nebular shell. It is noteworthy that dust can apparently exist within the C^{+3} zone.

The most obvious way in which dust manifests itself in PN is through its IR emission. Let L(IR) be the IR luminosity, corrected for the small amount of free-free radiation expected on the basis of the radio intensity. Let L(α) be the luminosity by Ly-α produced by recombinations within the ionized gas. The quantity L(IR)/L(α), the "infrared excess" (IRE), is a measure of the amount of dust absorption. The total energy available in the stellar and nebular spectrum which is not capable of ionizing hydrogen depends on the temperature of the star, but is about twice that in Ly-α for stars hotter than about

Yervant Terzian (ed.), Planetary Nebulae, Observations and Theory, 281-287.

50,000 °K. Hence, if $L(IR)/L(\alpha) > 3$, the dust must be absorbing ionizing photons. The IRE of many nebulae have been tabulated by Cohen and Barlow (1974). For some, it is less than unity, indicating that dust simply absorbs some of the Ly-α radiation. Bright nebulae which are dusty include BD+30°3639, IC 4997, NGC 6572, and NGC 6210. It must be noted that, except for NGC 7027, the published values of the IRE depend on an extrapolation beyond $\lambda = 22$ μm to the far IR (FIR), 30 μm $\leq \lambda \leq$ 1 mm. For NGC 7027, photometry in the FIR is available (Telesco and Harper 1977). Cohen and Barlow's extrapolation for NGC 7027 was remarkably good.

The general procedure for estimating the mass of dust in PN is to use the middle IR (MIR) data (say, 10 μm - 30 μm) to give estimates of the grain temperatures. With a grain model (material and size) assumed, the IR emission per grain is determined. The emissivity, when compared with the observed IR flux, yields the mass and optical depth of the grains. Most PN show, on the basis of this procedure, very small amounts of dust ($\leq 10^{-3}$, relative to hydrogen, by mass). The procedure is direct, appealing, and, in my opinion, extremely dangerous. The remainder of the discussion in this section will follow the important papers of Panagia (1975), Natta and Panagia (1976), and Panagia (1976), written in connection with H II regions but applicable to PN as well.

The problem arises from fitting two MIR fluxes with a temperature, and then assigning this temperature to any one grain. Instead, it is almost certainly true that there is a range of grain temperatures, even at a particular point in the nebula, caused by variations in grain sizes. This temperature range is clearly present in H II regions, where it is necessary to invoke at least two types of grains in order to fit both the MIR and the FIR data (Zeilik 1977, Panagia 1976). I would be very surprised if PN did not also have a range of sizes, and there is some evidence (to be discussed shortly) that at least NGC 7027 does. At any point in the nebula, the short-wavelength IR flux is emitted by the small, hot grains, and the FIR by the large, cool ones. A further complication is that there is also a radial distribution of temperature, caused by the decrease of the direct stellar heating with distance. The central heating of the dust is shown by the small angular size of the 10 μm images of four PN, compared to their radio and Hβ sizes (MacGregor et al. 1976). The assumption that the IR fluxes at two frequencies arise from the same grains is simply not true. The dust/gas mass ratio, then, can be estimated only in the context of a model of the grain size distribution and compositions. Observations of the FIR radiation are essential for the task, since its production requires the large, cool grains in which most of the mass is contained. For example, the models of Apruzese (1976) of NGC 7027, in which grains have one temperature at each point, require an increase in emissivity of the grains for $\lambda > 30$ μm in order to explain Telesco and Harper's FIR measurements. An unreasonably large optical depth and mass in dust were required. Apruzese suggests that cool dust outside the H^+ region would produce the FIR, but it is not easy to understand why the 20 μm size of the nebula is the same as the H^+ (radio) size in this case (Becklin et al.

1973). Having large, cool grains mixed with small, hot ones in the H^+ region explains the observations without requiring any rising emissivity beyond 30 μm (Panagia et al. 1977, Aannestad 1976).

THE COMPOSITION OF THE DUST

In the preceding paper, Dr. Balick reviewed the observations which suggest that carbonates and sulphates are responsible for some IR features (Bregman and Rank 1975), and that NGC 7027 is iron-deficient (Shields 1975). The dustier objects have such strong IR emission that one suspects that graphite, which has a large abundance but no obvious IR features, is present (Panagia et al. 1977). Shields (1977) and Panagia et al. 1977 have found NGC 7027 to be carbon-rich in the gas, suggesting that its precursor was a carbon star. Shields suggests a high C abundance for PN in general.

Many PN were observed in the UV by the ANS satellite (Pottasch et al. 1977), and the λ2200 feature was not correlated with the IRE, suggesting that internal dust in PN does not contain the material producing the λ2200 feature. Since graphite is well known to have a strong feature near λ2200 (and is widely supposed to be responsible for the feature in interstellar extinction), one might conclude that graphite is not present in PN. Such a conclusion is not justified. The absorption properties of a grain are strongly modified by particle size. Figure 1 shows a plot of $\sigma(abs)/V$, the absorption cross section per volume of various graphite grains, plotted against inverse wavelength. It is convenient to plot $\sigma(abs)/V$ because it approaches a limit for small particles. The optical constant were taken from Klucker et al. (1974) and Tosatti and Bassani (1970). For small grains (light solid line), we see the strong λ2200 feature (4.6 μm^{-1}), and a second, larger feature at about 750 Å (13 μm^{-1}). Note the decrease of the 13 μm^{-1} feature when the radius of the particle is 0.01 μm. At $a = 0.04$ μm, the 4.6 and 13 μm^{-1} features have disappeared. Hence, the lack of a λ2200 feature does not rule out graphite particles in PN.

One can easily see from Figure 1 how there will be a large difference in grain temperatures if graphite grains of, say, $a < 0.01$ μm and $a = 0.04$ μm are immersed in the same radiation field at a point in the nebula. Let us compare the relative wavelength dependence of the absorption of a large and of a small particle. In the FIR, they would have the same value of $\sigma(abs)/V$, since all particles with $a < \lambda/2\pi$ have a common value. However, at 750 Å, where the nebular radiation field is large, the absorption of very small particles is about 13 times greater than those at $a = 0.04$ μm (the ratio of the ordinates in Figure 1, at 750 Å). Hence, the small ones have about twice the temperature. Still larger particles will be colder than those with $a = 0.04$ μm.

One important point is that it is very likely that the dust in PN is not the same as that in the interstellar medium as a whole, for at least two reasons. Firstly, the ISM dust is composed of material ejected by a variety of objects, some of which have C/O > 1 and some with C/O < 1. Naturally, no such variety exists in a single PN. Secondly, grains in the ISM may be covered with mantles of ices, while it is difficult to imagine coatings on those in PN. The mantles have important effects on the absorption properties of the grains.

EFFECTS OF DUST ON THE IONIZATION STRUCTURE OF PN

A long-standing problem in models of PN has been that the strengths of lines of low stages of ionization (S^+, O^+, and N^+) are much weaker, as calculated by models, than they are observed to be (see, e.g. Miller 1974). Balick (1975) calculated models of PN with dust. Neither the temperature nor the ionization structure of the models was seriously affected by internal dust if the absorption cross section of the dust decreased with frequency, ν, or increased more slowly than linearly with ν. On the other hand, if the dust has an absorption coefficient increasing markedly with frequency (at least quadratically), the effects would be quite different. The abundance of the low stages of ionization are significantly increased over the no-dust models, and the nebular temperature drops. For a cross section increasing as ν^2, and half of the stellar photons absorbed by dust, the [O II] λ3727 strength is increased by about the required factor of 20 (Mathis 1977). Unfortunately, Figure 1 shows a strong absorption by graphite for hydrogen-ionizing photons ($\chi_H < h\nu < \chi_{He}$), and decreasing absorption for $h\nu > \chi_{He}$. Silicates have a similar behavior. Such dust would have little overall effect on the ionization structure of the nebulae, except to diminish the size of the ionized zone. No known material has an absorption cross section larger for helium-ionizing photons than for H-ionizing, but such grains are suggested on observational grounds in H II regions (Mezger et al. 1974).

Another way of enhancing low stages of ionization might be through having a large fraction (roughly half) of the nebular volume shadowed from the direct starlight by condensations, such as the famous ones observed in NGC 7293. Mathis (1976) showed that scattering of starlight by dust easily makes the ionization in the shadowed regions similar to that in the unshadowed. The scattering cross section of grains which are not in the Rayleigh limit ($a < \lambda/2\pi$) is comparable to the absorption cross section, and the average component of the scattered stellar photon into the shadow is about $(1 - \langle\cos\theta\rangle^2)^{\frac{1}{2}} = 0.6$, where θ is the scattering angle. It is therefore not easy to see how dusty PN, such as NGC 7027, can have important shadow effects. NGC 7027 is quite discrepant in the strengths of [O II].

THE DYNAMICAL ASPECTS OF DUST

Ferch and Salpeter (1975) have calculated models for the expansion of the PN shell containing dust. They found that dust is effectively coupled to the gas within the H^+ region because it is charged. The grains drag the gas with them as they are accelerated by radiation

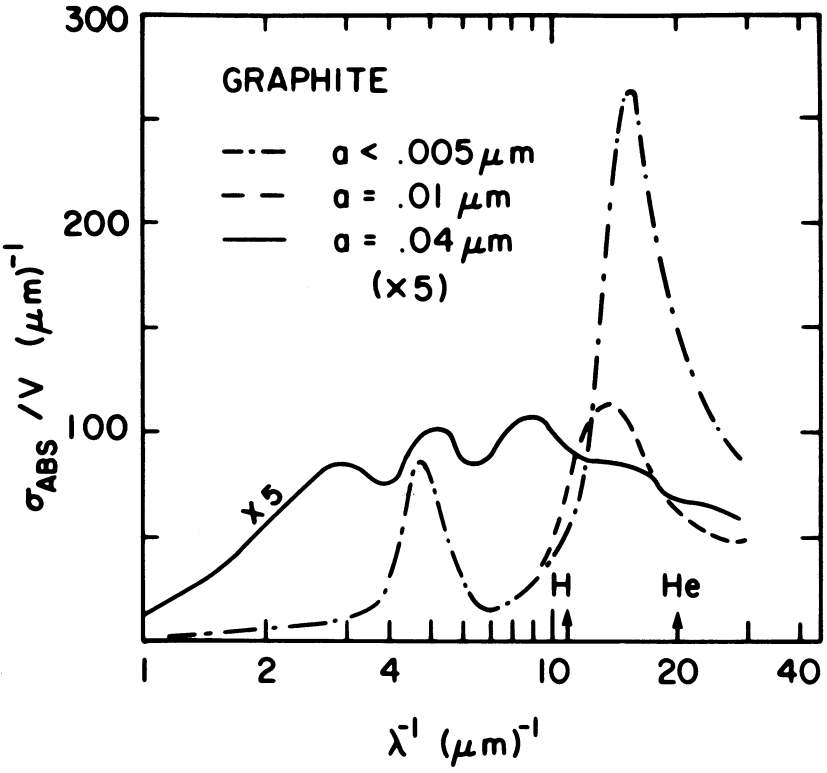

Figure 1. The absorption cross section per volume for graphite particles of various sizes, as a function of inverse wavelength. Dot-dashed: all particles smaller than 0.005 μm. Dashed: uniform distribution, $0.0093 < a < 0.013$ μm. Solid: uniform distribution, $0.037 < a < 0.043$ μm, multiplied by 5. Arrows: ionization edges of H and He.

pressure from the central star, creating the central cavity of the nebula. The outer parts of the nebula are not strongly affected by dust, but are primarily simply expanding into vacuum.

Finally, dust might be important for the whole evolution of the nebula by causing a thermal instability during the very early phases, when dust is the main coolant of the cold, neutral shell (Hunter 1973, Hunter and Nightengale 1974). The instability presumably leads to the condensations found in real objects. The question of the role of dust in the early history of the nebula is a complicated one, but it is important and should be investigated further.

It is a pleasure to thank Dr. Nino Panagia for useful conversations and Ms. Kathryn Saccone for her prompt and accurate typing of the manuscript, and the National Science Foundation for partial support.

REFERENCES

Aannestad, P.: 1976, Publ. Astron. Soc. Pacific **88**, 603.
Apruzese, J.: 1976, Astrophys. J. **203**, 177.
Balick, B.: 1975, Astrophys. J. **201**, 705.
Becklin, E. E., Neugebauer, G., and Wynn-Williams, C. G.: 1973, Astrophys. Letters **15**, 87.
Bohlin, R. C., Marionni, P. A., and Stecher, T. P.: 1975, Astrophys. J. **202**, 415.
Bregman, J. D., and Rank, D. M.: 1975, Astrophys. J. **195**, L125.
Cohen, M., and Barlow, M. J.: 1974, Astrophys. J. **193**, 401.
Ferch, R. L., and Salpeter, E. E.: 1975, Astrophys. J. **202**, 195.
Hicks, T. R., Phillips, J. P., and Reay, N. K.: 1976, Monthly Notices Roy. Astron. Soc. **176**, 409.
Hunter, J. H., Jr.: 1973, Astrophys. J. **180**, 99.
Hunter, J. H., Jr. and Nightengale, S. L.: 1974, Astrophys. J. **193**, 693.
Klucker, R., Skibowski, M., and Steinman, W.: 1974, Physica status solidi (b) **65**, 703.
MacGregor, A. D., Magro, C. S., Selby, M. J., and Whiteoak, P. A.: 1976, Astron. Astrophys. **50**, 389.
Mathis, J. S.: 1976, Astrophys. J. **207**, 442.
Mezger, P. G., Smith, L. F., and Churchwell, E.: 1974, Astron. Astrophys. **32**, 269.
Miller, J. S.: 1974, Ann. Rev. Astron. Astrophys. **9**, 331.
Natta, A., and Panagia, N.: 1976, Astron. Astrophys. **50**, 191.
Panagia, N.: 1975, Astron. Astrophys. **42**, 139.
Panagia, N.: 1976, in "Infrared and Submillimeter Astronomy" G. G. Fazio (ed.), D. Reidel Publishing Co., Dordrecht, Holland, p. 43.
Panagia, N., Bussoletti, E., and Blanco, A.: 1977, in "CNO Isotopes in Astrophysics", J. Audouze (ed.), D. Reidel Publishing Co., Dordrecht, Holland, p. 45.
Persson, S. E., and Frogel, J. A.: 1972, Astrophys. J. **182**, 177.
Pottasch, S., Wesselius, P., Wu, C.-C., and van Duinen, R. J.: 1977, Astron. Astrophys. **54**, 435.
Shields, G. A.: 1975, Astrophys. J. **195**, 475.
Shields, G. A.: 1977, Astrophys. J. in press.
Telesco, C. M., and Harper, D. A.: 1977, Astrophys. J. **211**, 475.
Tosatti, E., and Bassani, F.: 1970, Il Nuovo Cimento, **65B**, 161.
Zeilik, M. II: 1977, Astrophys. J. **213**, 58.

DISCUSSION

Aller: Graphite as it occurs on earth is normally produced under conditions of high pressure and does not occur in spherical form. Why not simply soot?

Mathis: I have no real objection to soot, rather than graphite, being formed in planetary nebulae. I have not considered whether it can explain the rather abrupt cutoff in the far-IR fluxes, which Dr. Panagia shows graphite can. However, I feel that the interstellar medium does have graphite which contributes the λ2200 feature. Hence, it seems simpler to me to suppose that graphite rather than amorphous carbon is formed in planetary nebulae.

Field: Why do you support graphite on the grounds that it is featureless in the IR, when the observed spectrum does in fact have strong features?

Mathis: The far-IR flux requires very cold particles in the H^+-zone, implying a mass of >1% that of hydrogen. Only the very high C abundance can supply this mass. The IR features can be supplied by trace impurities.

Kwok: About the absence of the silicate feature, I think it is quite possible that there are two dust components. One is cold and far away from the central star, produced by the red giant before the ejection of its outer atmosphere. We know that many red giants are losing mass, possibly by radiation pressure on dust. This dust component is so cold that the silicate feature is unobservable. On the other hand, we have hot dust formed near the central star, in the ionized region. The chemical composition of this component we do not know. On the whole I do not think we can rule out silicate grains in planetary nebulae.

Dopita: The absence of a silicate feature may not be evidence of the absence of silicates. Hyland and Robinson have made calculations for a circumstellar dust shell geometry which show that near a critical dust temperature this feature disappears, changing to emission at high temperature and absorption at lower. Since the critical temperature is of order 100°K, emission may be absent.

Mathis: Neither the 9.7 μ nor the 18 μ silicate feature is observed. I don't see how both features could disappear together. Furthermore, no planetary nebulae shows either of them.

Forrest: Are there any observations of polarization which may bear on the question of dust in or around planetary nebulae?

Mathis: I don't know of any such observations.