SYMPOSIUM CONCLUSIONS II

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Dr. Osterbrock has given a comprehensive summary of the Symposium. I will discuss a few topics which seemed particularly interesting to me as a non-specialist: dust, the fate of pre-planetary ejecta, and inhomogeneities. Let me begin by describing a simple model of the planetary nebula (PN) phenomenon, which is suggested by the discussions we have heard at this Symposium, and which provides the framework for my other comments.

The red-giant precursors are known to have winds, in which about $1M_\odot$ is ejected at about 10 km sec^{-1} in about 10^6y. In many of these red-giant ejecta (RGE) one observes the 10-micron silicate emission feature ("dust bump") characteristic of dust grains heated by the red giant. The presumption is that this dust has formed in the RGE; this is not unexpected, because thermodynamic calculations show that in a gas cooling by expansion, the first particles to form in an oxygen-rich ($C/O < 1$) cosmic mixture are silicates.

Deeper layers of the red giant are exposed during this process. As they approach the highly condensed core, the surface layers of the star become unstable, resulting in the rapid ejection of material in one or more pulses. These ejecta, presumably cool at first, form the pre-planetary nebula (PPN), for which very plausible candidates are the luminous infrared sources discussed by Zuckerman at this Symposium.

As the PPN leaves the star, an extremely hot surface is exposed. The UV from this surface is initially absorbed by the PPN material near the star. However, when the density in the PPN falls to a sufficiently low value, an ionization front moves rapidly through it; CRL 618 is a candidate for this stage. The unusual object V1016 Cygni discussed by Purton and Feldman and by Ahern et al at this Symposium is a related object, probably having a shell with mass much less than that of a PN. Ultimately the central star or nucleus (NPN) becomes visible, and the ionized gas of the PPN is observed as a PN.

Various observational evidence indicates that individual PPN, PN, and NPN are often carbon-rich ($C > O$). In the case of PPN candidates,

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the evidence is based on optical, infrared, and radio molecular spectra. While the situation is not entirely clear for PN, the evidence from UV resonance lines, CII recombination lines, and CI forbidden lines taken together tends to favor C > O. And in certain classes of NPN, the same is indicated by optical aspects.

That the deeper layers should be carbon rich is not unexpected theoretically, because models indicate that helium burns to carbon in the stellar core. Presumably the apparent progression from C < O to C > O as the deeper layers are revealed reflects the degree of mixing of the envelope with the carbon-rich core as a function of depth.

With this background, let me discuss dust in planetaries. We heard at this Symposium that continuum infrared emission is a ubiquitous feature of planetaries and that there are several infrared bands (3.3 μ, 6.2 μ, 11.3 μ) which are unidentified.

As explained by Mathis at this Symposium, it is probable that the IR continuum is due to graphite particles heated by the NPN. Several lines of argument support this view:

a) Particles are needed to explain the IR continuum, but silicate features are not observed.

b) Thermodynamic calculations show that the prime condensate in a cooling cosmic mixture with C > O is graphite.

c) In the PPN candidates discussed by Zuckerman, dust is present in large amounts, and C > O. As the gas is observed to be expanding at 10-20 km $\sec^{-1}$, graphite particles might well be forming there.

d) Graphite particles, being highly refractory, can survive in the hostile environment of the PN.

e) As discussed by Mathis, the absence of the well-known graphite absorption band at 2200 Å requires that the particles be larger than 0.04 μ.

Two different models have been proposed. Forrest assumed sizes ≤ 0.1 μ and found that $2.5 \times 10^{-2} M_\odot$ of graphite would be required to explain the IR emission from NGC 7027. Alternatively, Balick and Panagia fit the data with 1 μ particles, having a total mass of 10^{-3} $M_\odot$ (both estimates being based on d = 1.8 kpc). In either case, the amounts are large; with the standard cosmic abundance of carbon (3.6 x 10^{-3} by mass) a typical PN of 0.16 $M_\odot$ would have only 6 x 10^{-4} $M_\odot$ of carbon. If we denote the enirchment factor of carbon by f, and the fraction going into graphite grains as g, the above data suggest that fg is between 1.6 and 40. Even if g approached 1, the presence of graphite in the required quantities points to carbon enrichment of the PN (f > 1). Values of the order f = 10 discussed at this Symposium appear to be consistent with the IR observations if g is of the order of unity. Alternatively, the dust is located in the RGE with $M \sim 1\ M_\odot$, but this would be contrary to the assumption that $C < 0$ in the RGE.

The dust in PN has a number of important consequences for PN themselves. By absorbing ionizing photons, it has a major effect on the calculation of ionization equilibria. By scattering ionizing photons, it prevents neutral shadows from forming behind neutral condensations. By absorbing resonance-line photons, it modifies the abundances inferred from observations of recombination lines. By absorbing momentum from the radiation field it can, by virtue of its strong coupling to the gas, accelerate it outward, creating the hollow-shell structure observed in many PN. For these reasons, as well as others, it will be necessary to understand the composition and distribution of dust in PN in order to create viable models for them. To me, at least, this represents a major new input for the classical PN problem.

The graphite dust in PN may also be important on a galactic scale, for we know from the interstellar λ 2200 band that graphite is a major component of the interstellar medium near the Sun. I have estimated (Field 1974) that 60% of the interstellar carbon in front of the well-observed star ζ Oph is in the form of graphite. A very similar result has been derived by Mathis et al (1977) on the basis of much more sophisticated model fitting. If following Salpeter we take the mass of the interstellar medium as $5 \times 10^9\ M_\odot$, and if the cosmic abundance of carbon is 3.6×10^{-3} by mass, there is $1.8 \times 10^7\ M_\odot$ of graphite. Where did it come from?

Previous discussions of this problem have suggested that the source of interstellar graphite is carbon stars. Alternatively, interstellar graphite may originate in PN. We have heard at this Symposium that the rate of PN is roughly $1\ y^{-1}$, giving a rough estimate of 10^{10} PN over the age of the Galaxy. To supply $1.1 \times 10^7\ M_\odot$ of interstellar graphite, we would need $1.1 \times 10^{-3}\ M_\odot$ per PN; this in fact lies in the range estimated by the IR observers at this Symposium ($1\text{-}25 \times 10^{-3}\ M_\odot$) and corresponds to $f_g = 2$. These figures seem entirely reasonable.

There appears to be a problem with this suggestion, however. We have already pointed out that the λ2200 band is not observed in PN. This would require that the particles are larger than 0.04 μ. However, in the ISM the band is observed, and this requires small particles. According to Mathis et al (1977), the ISM observations are best explained by graphite dust having a range of particle sizes down to a few times $10^{-2}\ \mu$. The best fit is obtained with a power-law distribution $f(a) = C_1 a^{-3.5}$, which corresponds to a mass distribution $f(m) = C_2\ m^{-1.8}$. Thus, if PN are the source of IS graphite particles, something must break them into smaller-size particles. Interestingly enough, one often finds that grain-grain collisions result in a power-law distribution, as in the solar system, where the observed distribution of meteorites corresponds to $f(m) = C_3 m^{-2}$ for stony meteorites and $f(m) = C_4 m^{-1.7}$ for irons (Hawkins 1964). Spitzer (1977) has shown that shattering can occur if the IS dust - gas mixture is overrun by a powerful shock wave, such as would originate in a supernova.

This picture yields certain predictions. Bear in mind that C > 0 indicates helium burning, with the consequence that ^{13}C is abnormally low. Since graphite can form only where C > 0, we expect the ^{13}C in the graphite to be abnormally low, and, since solar-system carbon presumably represents a sample of interstellar matter which includes both graphite and gas-phase carbon, interstellar gas must be richer in ^{13}C than the solar-system ratio $^{13}C/^{12}C = 1/90$ would indicate. If the solar system originated in a cloud containing 60% graphite, in which all the ^{13}C was in the gas phase, then $^{13}C/^{12}C = 1/36$ in the gas phase. Presumably this should be true of the ISM generally, so our first prediction is that radio observations of ^{13}C in interstellar molecules should show it to be enriched to the level of about 1/36 of ^{12}C.

A further prediction concerns the observation of molecules in PN. If C/O > 1, we would expect to see no O-rich molecules because the O should all be in CO. Thus, H_2O and OH should not be observed in PN. The IR emission features at 3.3 μ, 6.2 μ, and 11.3 μ could well originate in C-rich solids. Appropriate candidates include the high-molecular weight organic residue found in carbonaceous chondrites (Anders 1971).

Both theoretically and observationally, the RGE which precede the PN phenomenon usually (but not always) have C < 0. Hydrogen burning in the CNO cycle should increase ^{13}C in this component, in harmony with observations of red giants. In NGC 7027, the CO is enriched to $^{13}C/^{12}C \sim 1/20$; the large extension of the CO region suggests that we are observing the RGE. These facts suggest that some of the gas-phase carbon in the ISM originates in RGE. The idea that interstellar gas is enriched in ^{13}C is in harmony with this suggestion.

This brings us to a discussion of the RGE. We expect them to be oxygen rich, and that the silicon in them should be largely condensed into silicates. If they supply a significant fraction of the ISM (as they will if their masses exceed a few tenths of a solar mass), they may be a primary source of interstellar silicate grains, and may account for the fact that something like 90% of interstellar silicon is in dust (from Copernicus observations). Woolf has long maintained that this is the case (Woolf 1974). If so, the PN phenomenon in general, including the RGE precursor, could well account for a substantial fraction of the mass in the ISM, and could account for the fact that it contains both silicate and graphite particles.

One wonders about the fate of RGE after the PN phenomenon starts. We have had little discussion of this at the Symposium, but there seems to be no escape from the conclusion that each PN must be surrounded by an O-rich cloud of roughly $0.5M_\odot$, which is the diffuse remains of the RGE. If we take 10 km sec^{-1} and 10^6y as typical of these objects, in the absence of surrounding ISM we predict that the outer edge would be at 10 pc, and that the density would be given by

$$n = 0.15 \; r_p^{-2} \qquad (1)$$

where r_p is the distance from the PN in pc. This discussion ignores mixing with the local ISM, which probably dominates beyond 1 pc or so. However, equation (1) predicts considerable densities ($\gtrsim 0.5\ \text{cm}^{-3}$) and masses ($\lesssim 0.05\ M_\odot$) within ≃ 1 pc. Such remnants may be observable. The gas should be ionized if the PN is optically thin at the Lyman limit. The speed of an ionization front, given the inverse-square density distribution, is

$$V_{IF} = V_{RGE} \frac{F(h\nu,NPN)}{F(H,\ RGE)} \qquad (2)$$

where v_{RGE} is the velocity of the RGE (~ 10 km sec^{-1}), $F(h\nu,NPN)$ is the flux of ionizing photons from the central star (~ $3 \times 10^{46} \text{sec}^{-1}$) and F(H, RGE) is the atomic flux from the precursor red giant (~$1.5 \times 10^{43}\ \text{sec}^{-1}$). Hence $v_{IF} \simeq 20{,}000$ km sec^{-1}, and the region inside 1 pc should be ionized in less than 10^3y after the PN itself. The emission measure at a projected distance r_p (in pc) from the center should be

$$EM = 0.03\ r_p^{-3} \qquad (3)$$

The ejection of the PN overtakes the RGE out to a distance r(PN) ≃ 0.1 pc, so $r_p > 0.1$.

One wonders about the giant halos discussed at this Symposium by Mathews. Could these be related to RGE? Some of them appear to be highly spherical and sharp-edged HII regions with a radius several times r(PN). The sharp edge is unlikely to be an ionization front, because such a front is very transitory, as shown above. Rather, it is more likely to be a disturbance within a completely ionized RGE. In discussions with Mathis, Woolf, and Mathews, at this Symposium, it was suggested that it could be a shock front driven into the RGE by the PN, which typically expands at 30 km sec^{-1}, sufficient to overrun supersonically the RGE expanding at 10 km sec^{-1} (since the isothermal speed of sound at T = 7600° K is 10 km sec^{-1}). One finds that at the moment of detachment of the shock front, it would travel at 34.1 km sec^{-1} into the expanding RGE, compressing it a factor of 5.8. One expects this compression factor to be reduced somewhat as the shock expands; if we take a factor 5 as representative at a distance r_p of 0.3 pc, the expected emission measure tangentially through the shock from (3) would be about $0.03 \times 5^2 \times (0.3)^{-3} = 30$, which is barely detectable. If the observed halos are in fact shock-excited RGE, they should have $C < 0$; it would be interesting to test this, although it will be difficult to do so in view of the low EM. The expected visual extinction of the PN due to the RGE is only $0^m.003$, and the corresponding 10-μ silicate absorption feature would therefore be undetectable.

Let me close by mentioning future opportunities in PN research. Clearly it is important to study the dust by all means possible. Beyond that, it seems to me as a nonspecialist that many problems revolve around an understanding of the inhomogeneities in PN. It is necessary to correctly take them into account if one is to understand the emission spectrum and to derive reliable abundances. To the extent that molecules are located in cold condensations, one has the possibility of deriving abundances from radio line observations. Finally, the very existence of condensations may tell us something about the earlier history of PN. For example, they may be residues of the PPN, which are observed to be cold and dense, and to contain molecules.

Theoretically, the equations governing cold condensations embedded in a PN, and the resulting trails extending away from the NPN, are well known. However, solving them accurately is a major computational task. The advent of fast computers capable of solving time-dependent radiative hydrodynamics in two dimensions will be helpful here. In particular, it would be very interesting to study a system with axial symmetry around a radial line to the NPN.

A major theoretical development is the realization that charge exchange reactions between ions and H and He atoms are likely to play an important role in some PN, as described by Dalgarno at this Symposium. The condition for these reactions to be important is that ions which require more than 1 Rydberg to ionize coexist with neutral H or He. This occurs to a small degree throughout the nebula, but is particularly important in transition regions between HI and HII, as would occur at the rims of neutral condensations. If the NPN is particularly hot, its radiation can penetrate relatively far into the condensations, ionizing minor constituents, while leaving HI relatively unaffected because of its small photoionization cross section at high energy. As we heard from Pequignot at this Symposium, better agreement with observation is secured if charge exchange with H°is rapid for C^{+3}, N^{+2}, N^{+3}, 0^{+}, 0^{+2}, S^{+}, S^{+3}, and Ne^{+2}. As we heard from Dalgarno, the reactions for C^{+3}, N^{+2}, N^{+3}, and 0^{+} have either been calculated or estimated to be fast. S^{+} and S^{+3} are uncertain, and 0^{+2} and Ne^{+2} are estimated to be slow. It appears that further effort on this problem, both observational and theoretical, is well worthwhile.

Observationally, two new developments promise more information on condensations. Panoramic photodetectors, capable of imaging PN in selected emission lines, can digitally record line intensities over the surface of the nebula on a linear scale, making possible rapid analyses of density and temperature as a function of position. An admirable start on such studies has been made by the Imperial College group, as reported by Worswick at this Symposium. As reported by Bignell, the advent of the VLA, capable of making radio images of PN with better than 1" resolution, will also be a large advance, because such images will be free of the confusing effects of extinction, both within the PN and in front of it.

Finally, we may look forward to additional UV telescopes, starting with IUE this year, and culminating with the Space Telescope in 1983. The latter will not only provide information on the UV emission of PN and their central stars, but also permit imagery in various visible spectral lines with an angular resolution of 0".1. At a distance of

1 kpc, this will permit study of features as small as 5×10^{-4} pc, or 1/200 the size of a typical PN. At the distance of the Magellanic Clouds, 50,000 pc, a 0.1 pc radius PN will subtend an angle of 0''.4, and will therefore be resolvable. By doing so with the Space Telescope, we should get a direct test of the present distance scale for PN.

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