Dying stars and reborn dust*

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I am happy to help honor the memory of J. Robert Oppenheimer at this occasion. I started my scientific career as a quantum field theorist and, on numerous pilgrimages to the Princeton Institute, I was inspired and helped by Oppie's enthusiasm and insight. Although Oppenheimer is not so well known in astrophysical circles, he and his associates actually did much of the pioneering work on the gravitational collapse and structure of neutron stars long before any were discovered. Neutron stars lie at the heart of supernova remnants which I will discuss at the end of this report. My topic deals with one aspect of the symbiotic relationship between stars on the one hand and interstellar gas and dust on the other—the effect of dying stars (more specifically, of planetary nebulae and of supernovae) on producing and replenishing dust grains. I shall mainly review the current status but end with a speculative conjecture.

In spiral galaxies like our own, interstellar dust occurs together with interstellar gas in a disk a few hundred light years thick. Some information on the optical properties of these dust grains has been available for a long time from studies in the visible spectrum of reflection nebulae and of the extinction and polarization curves for light from distant stars. This information has been greatly augmented in the last decade or so by infrared observations and by the two OAO satellites working in the ultraviolet. Detailed reviews were presented by Greenberg (1973) and by Woolf (1973) at a recent symposium and some of the gross features of the data are shown schematically in Fig. 1, where the extinction efficiency $Q(\lambda)$ at wavelength λ (multiplied by λ) is plotted against λ: The two "humps" in the infrared are generally agreed to be absorption features common to most types of silicate grains, and the peak near $\lambda \sim 2{,}500$ Å is thought by some to be due to small graphite grains, but this assignment is still controversial. The most prominent interstellar dust grains must have radii a of order 0.03 μ to 0.2 μ, but the further rise of $\lambda(Q)\lambda$ in the far ultraviolet indicates the presence of some very small grains with $a \lesssim 100$ Å.

If one assumes some specific model of the distribution of sizes and chemical composition of the interstellar grain, which fits the *shape* of the observed extinction (and polarization) curves, one can calculate (Greenberg, 1974) the total amount of grain material required to fit the *magnitude* of the extinction. Without making specific model assumptions, one can still derive *lower limits* to the required amount of grain material from the Kramers–Kronig dispersion relation (see Purcell and Pennypacker 1973; Caroff *et al.*, 1973). It is of interest to compare the conjectured amounts of grain material with the amounts in grains and gas combined given by the so-called "cosmic abundances" (relative to hydrogen, whose density in interstellar space is known fairly well from 21 cm observations). These "cosmic abundances," obtained mainly from the solar atmosphere where there are no grains, are given in the first line of Table I for a few of the most relevant elements (nitrogen is slightly less abundant than carbon; silicon has comparable abundance to magnesium, which is the most abundant metal to form silicates). Analyses of the extinction data show that much of the Mg and Si in interstellar space must be in the form of grains (if the infrared "humps" are indeed due to silicates). Furthermore, there must be more material in addition to silicates in the grains (to fit the ultraviolet data). Most of the additional material is thought to be in compounds derivable from the "ices" of abundant elements, CH_4, NH_3 and H_2O. The full amount of these ices obtainable from the cosmic abundances is *not* absolutely required, if most grains are near the optimum size (Greenberg, 1974). However, we have no direct evidence on how much C, N, and O is locked up in very small ($a < 50$ Å) or very large ($a > 0.5\ \mu$) grains whose optical efficiency is low.

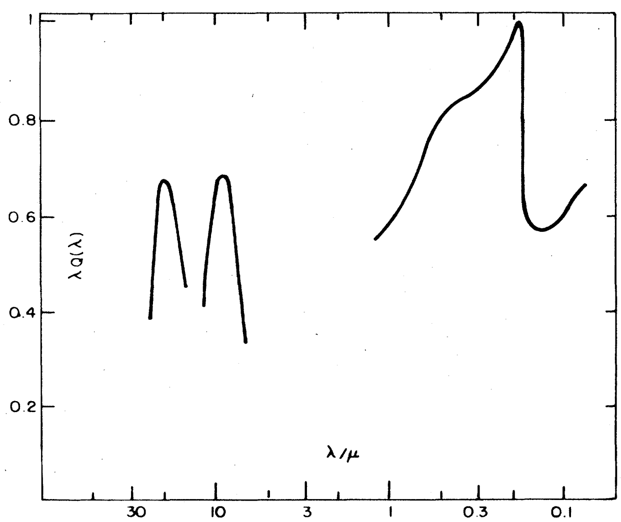

FIG. 1. The extinction efficiency $Q(\lambda)$ at wavelength λ (multiplied by λ) of typical interstellar dustgrains plotted (in arbitrary units) against λ.

To summarize present views on the chemical composition and abundance of interstellar dust grains (see also Aannestad and Purcell, 1973): There is plenty of observational data and it is clearcut whether a given theoretical model fits the data or not. However, there is no sufficient observational data to be able to derive a unique model from it. Much of the condensable material (such as the metals, C, Si, etc.) in interstellar space must be in the form of grains, but the data does not specify whether "much" means 25% or 100%.

TABLE I. The "cosmic abundance" A_c, by numbers of atoms relative to hydrogen, for a few elements and the ratio of the abundance A_{gas} in the interstellar gas to A_c.

	C	O	Mg	Al + Ca
$\log_{10} A_c$	−3.5	−3.2	−4.5	−5.5
$\log_{10} A_{gas}/A_c$	−1.2	∼−0.5	−1.2	−(2.5 to 4)

* This paper is based in part on a talk delivered at the J. Robert Oppenheimer Memorial Prize Ceremonies on January 9th, 1974, at the Center for Theoretical Studies, University of Miami, Coral Gables, Florida.

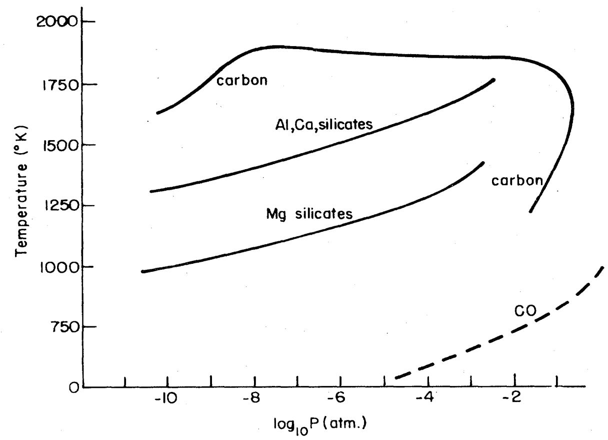

FIG. 2. A schematic pressure–temperature phase diagram: Carbon monoxide is stable above the dashed curve; for carbon-rich material graphitelike grains condense out near the curve labeled carbon; for oxygen-rich material various types of silicates condense out between the two curves labeled silicates.

The amount of various elements in the form of gas atoms (or of simple molecules) in interstellar space can be measured by means of optical absorption lines and compared with the amount of hydrogen. Much of this data comes from uv observations with the Copernicus satellite (Morton *et al.*, 1973; Spitzer *et al.*, 1973), but ground-based observations are also involved (White, 1974). The relevant data and its significance was summarized recently by Field (1973, 1974) and a few examples are given in the second line of our Table I. The results are not yet quantitatively reliable, but suggest the following rather surprising trends: (i) Many elements are slightly underabundant in the interstellar gas (compared with cosmic abundances), such as O; (ii) a few, including C and Mg (also Mn and Fe) are underabundant by slightly more than a factor of 10, and (iii) especially Ca and probably also Al and Ti are underabundant by a factor of a thousand or more!

Before discussing the possible significance of the abundance data, we need the thermochemical information summarized schematically in Fig. 2: To form grains from the vapor phase we need temperature in the range of 1000° to 2000°K. Above the dashed line labeled CO in Fig. 2, carbon monoxide is extremely stable in gaseous form. Therefore, whichever of C and O has the lower abundance (by number of atoms) is locked in the gas phase as CO and only the more abundant partner is free to form grains. Usually (see the cosmic abundances in Table I) O is slightly more abundant than C and the most refractory solids which can be built from oxygen-rich material are the various silicates. As indicated in Fig. 2, minerals involving calcium and aluminum silicates condense out at the highest temperature. As material is cooled, these minerals will condense out first to form very small grains by homogeneous nucleation; upon further cooling the more abundant magnesium silicates will condense using these very small grains as condensation nuclei (Salpeter, 1974). In a small (but not negligible) fraction of stars, carbon is more abundant than oxygen, and the most important grains formed are carbon-rich particles with a structure similar to graphite but probably with a small admixture of hydrogen.

The possibility of making dust grains in the atmospheres of cool stars was already raised some time ago by Hoyle and Wickramsinghe (1962), and by Donn and Stecher (1965). The situation is particularly simple if the star's effective surface temperature T_e is close to or even below the condensation temperatures for the solids ($T_e < 2000°K$, say). If the star's luminosity L is sufficiently large so that radiation pressure acting on the grains exceeds the gravitational force on grains and gas (H and He) combined ($L \gg 10^3 L_0$, say), grains are not only made but also injected into interstellar space by the resultant outflow. Such large values of L and small values of T_e require very large values of stellar radius R, reached only by the coolest supergiants (especially near the greatest expansion of long-period variable stars, e.g. Mira variables). The situation is particularly favorable for the rarer carbon-rich stars, since graphitelike carbon particles condense at relatively high temperature and have a high opacity which makes radiation pressure more important (Fix, 1969). The theory is more complicated and uncertain for the production of silicate grains in oxygen-rich stars (Kamijo and de Jong, 1973), but fortunately there is some observational evidence from infrared emission features in the spectra of cool stars for the presence of silicate grains (Jennings and Dyck, 1972; Cohen and Gaustad, 1973; Woolf, 1973). The total outflow rate of grains from such cool supergiants is not clear yet, and other sources of grain production are also of interest. Very young and very massive stars (Hoyle, Solomon, and Woolf, 1973) may also contribute, but stars of moderate mass (a few solar masses, say) are probably most important. During some late stages of their evolution a copious outflow of gas takes place, which is not *caused* by grains but grains can form subsequently as the outflowing stream of gas cools.

Only a moderate amount of moss loss is thought to occur when a star with a helium core first evolves away from the main sequence into the red giant region. The situation is more favorable during the later stages of evolution, when a star has a small core rich in C, O and Ne, a helium-rich mantle, and a hydrogen-rich outer envelope. This envelope expands, the luminosity is quite large ($L \gtrsim 10^4 L_\odot$), and at some stage the envelope becomes unstable to hydrodynamic outflow. This outflow is the basis of the formation of a planetary nebula, where a mass of the order of $\sim 1 M_\odot$ is ejected over a period of about a thousand years. Recent observational data (Cahn and Kaler, 1971) on planetary nebulae suggest that a large fraction ($\gtrsim 1/2$) of all "star deaths" occur only after the star passes through this phase. The stellar remnant in such cases is a white dwarf, contrasted with the formation of a neutron star during a supernova event. Supernovae occur less frequently than planetary nebulae by a factor of about 100; we shall nevertheless return to a conjecture about the effect of an expanding supernova shell on the surrounding interstellar medium.

During the ejection of a planetary nebula shell the material has to flow out a few stellar radii before it is sufficiently cool for all the silicates to condense out. The gas density is rather low (and not well known theoretically) at this stage, and purely theoretical calculations of the efficiency of grain formation are not yet very reliable (Salpeter, 1973). Fortunately, direct observational evidence on infrared emission from planetary nebulae indicates the presence of radiating dust grains (probably silicates) more than 10^4 years after the ejection of the nebula shell (Woolf 1973; Leibowitz, 1973). Planetary nebulae are probably one of a small number of major sources for interstellar silicate grains, and current estimates for the total production rates of such grains are encouraging: The total amount of material processed through magnesium silicate grains, for instance, in the lifetime of our galaxy ($\sim 10^{10}$ years) may even be a few times larger than the present amount of Mg and Si in interstellar space. Such an inequality is possible because more than 90% of the total mass of our galaxy has been processed from interstellar material into stars and many grains formed earlier have been used up in star formation.

Estimates for grain production in stellar atmospheres and in planetary nebulae indicate that a fairly large (but *not* overwhelmingly large) fraction of the interstellar Mg, Si, Ca and Al, say, should be in the form of grains. This estimate would predict a small degree of underabundance of these elements in the interstellar *gas* but is incompatible with the *very* large degree of underabundance observed for Ca and Al (see Table 1). Furthermore, the *moderately* large underabundances in the gas of C and O are also incompatible (Greenberg, 1974; Field, 1974) with the assumption that grains are grown only in stellar atmospheres and planetary nebulae without further reprocessing. As mentioned earlier, a substantial fraction of the C and O in the outflowing material is in the form of gaseous CO which does not condense easily (and is later photodissociated into atomic C and O); more generally, the various "ices" cannot be made in this manner. In fact, planetary nebulae older than about 10^4 years provide a direct illustration of the dilemma: The nebula shell is optically thin to ultraviolet radiation from the central star of the nebula; theoretically, only refractory materials like silicates (or graphite) can survive in solid form, but not the more volatile "ices" made from C, N and O. Observationally, we have direct evidence (Peimbert, 1971) for the presence of nitrogen and oxygen in gaseous atomic form in these planetary nebula shells which eventually must get mixed in with the interstellar gas. One also has to contend with an additional difficulty: In some regions of interstellar space, conditions are such that sputtering will partially destroy grains, which should also feed more atoms into the interstellar gas (Aannestad, 1973).

Of the various ways out of this dilemma, one is connected with star birth and another with star death: Stars are often born in a group out of a massive, dense interstellar cloud of gas and dust. Only a small fraction of the cloud's mass goes into stars, and the rest of the cloud is re-expanded by the radiation from the newly formed stars. It has been suggested (Field, 1974) that such cloud material just before its re-expansion may be a favorable site for replenishing silicate (or graphite or iron) grains and for growing ice mantles on them. It is hard to investigate this suggestion quantitatively in our present state of ignorance on the details of star formation. High gas density favors and high stellar luminosity hinders the process, and we do not know the density–temperature history sufficiently well. We finally turn to another tentative conjecture which involves one form of star-death, namely supernovae–or, more correctly, the effect of the expanding supernova shell more than 10^5 years after the actual explosion.

Supernova explosions occur about one hundred times less frequently than planetary nebulae, and the ejected shell

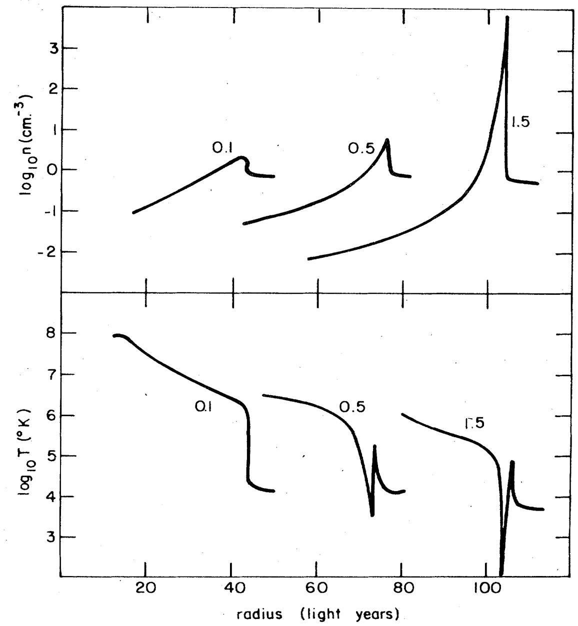

FIG. 3. Theoretical blast-wave results (with radiative losses) for density n (in H atoms cm^{-3}) and temperature T (in °K) plotted against radius for various times t after a supernova explosion. An explosion energy $\sim 5 \times 10^{50}$ ergs and an interstellar medium with $n \sim 0.5$ was assumed. Curves are labeled with the value of t in units of 10^5 years.

mass per event is comparable ($\sim 1 M_{\odot}$). The mass ejected in the shell is of little direct importance, but the kinetic energy in the explosion is about 10^4 times larger than in a planetary nebula, and the explosion causes a blast wave to propagate out through the interstellar medium. A number of analytic studies have been made (Cole 1972), as well as numerical calculations (Chevalier, 1974; Straka, 1974; Mansfield and Salpeter, 1974) to follow the progress of the blast wave, including the effects of hydrodynamics and of radiative cooling. At approximate pressure equilibrium, radiative cooling is faster at *lower* temperatures (at least for $T \gg 10^{4}$°K) and this results in a "thermal instability": After less than 10^5 years a thin shell forms near the outer edge of the blast wave, which gets cooler, denser and thinner (but *more* massive) as time progresses (somewhat like a snow-plow plus a compressor). The density and temperature profiles at various time epochs are shown in Fig. 3, schematically, for a typical core. Note in particular the fairly hot shock region, just outside the cool shell, through which the interstellar gas and dust must pass before becoming incorporated into the dense shell. Some sputtering of grains may take place in this shock-region, but this becomes unimportant when the shock-temperature drops well below 10^{5}°K (the grain temperature is orders of magnitude lower). We then have a rather long period (of order 10^6 years) when interstellar gas and dust is compressed to rather high densities (up to $\sim 10^4$ H atoms/cm^3, say), mostly at temperatures of $\lesssim 100$°K. This condition *may* be quite favorable for condensing out more material from the interstellar gas (remaining metals as well as various "ices"). Unfortunately, this conjecture is still quite controversial. Although an appreciable fraction of interstellar matter *may* be in such thin, dense shells, the theoretical uncertainties are great for such old supernova remnants, due to uncertain effects of magnetic pressure and of turbulence. It is also difficult to observe such shells optically because they are so thin, but it may nevertheless prove possible to detect them in the form of thin rings projected against the sky where dust absorption makes background stars appear faint (a kind of "negative stellar ring").

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