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Star Dust

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Dust is a major constituent of the universe. Even a casual inspection of deep sky photographs will verify its existence in obscuring clouds, lanes, globules, and suggestive forms like the famous Horsehead nebula in Orion (see cover). All but the nearest stars are observed behind a column of dust that dims their visual brightness and reddens their energy distributions. In interstellar space dust occurs as grains micrometers and less in diameter and, although it contributes only 1 percent of the mass of the medium, it is almost entirely responsible for the extinction of starlight in the visible region of the spectrum. The hydrogen and helium in space supply the mass, but the dust is responsible for the opacity. By comparison, the earth's atmosphere is a million times cleaner than the interstellar medium—only one part in 10^8 by mass of the atmosphere is particulate aerosols—and if the interstellar medium were compressed to atmospheric density, 1 meter of "air" at sea level would become opaque to light.

The dust is something of an embarrassment in cosmology. We do not believe that dust could have been an important constituent of the early universe. On the other hand, we rely on the existence of dust and gas condensations to collapse to form stars, stellar systems, and planetary bodies. We search for sources capable of creating the complex solids from which the planets, including the earth and the moon, can be formed in a cosmological environment dominated by hydrogen and helium. There are two problems. The first is to form the heavy elements, and the second is to assemble them into molecules and disperse them into space.

Gamow (*1*) originally believed that nuclear reactions in the big bang could make the elements of the periodic table, but his idea failed because of the instability of beryllium-8, which produces a barrier to the formation of heavier elements. Burbidge *et al.* (*2*) resolved the problem of showing that the elements can be formed in a more leisurely way by nuclear cooking in dense stellar interiors. The formation of the heavy elements has become a part of the drama of stellar evolution. The last act in this drama for all stars more than twice as massive as the sun is the violent implosion that forms a supernova. This last act can be postponed if the star has enough angular momentum, or it can be circumvented if the star is able to lose enough material to drop below the critical mass. Stars that do become supernovae enrich the interstellar medium with their nuclear products (heavy elements), but the number of these events is too small to supply the material required by newly forming stars. As specific examples, the Crab nebula is the remnant of a star that became a supernova, and the young (1 to 10 million years old) hot stars in Orion are the prototypes of the forming stars that must be cultured from interstellar material.

For every star destined to become a supernova there are hundreds that lose their mass placidly by blowing it away in their stellar winds. Recent observations at a variety of wavelengths have shown us that certain classes of stars (luminous cool giants and supergiants) may condense the high-melting-point products of their nuclear creations as molecules in their cool extended atmospheres. These molecules form grains, which are propelled by the stellar winds into the interstellar environment. The constituent elements of the dust such as carbon, oxygen, magnesium, and silicon must of course, have been previously manufactured by nucleosynthesis in dense hot stellar interiors. The outer atmospheres of the giant stars represent an environment where refractory compounds can condense. The pressure of the light from these luminous objects can disperse the dust into space. In short, there is a clean way to make dirt.

Stars with Dust Shells

One of the first observational indications that dust shells exist was the strange light variation of the star R Corona Borealis (R CrB). Most intrinsic variable stars show a quasi-periodic light variation, which is believed to reflect a thermodynamic oscillation of the star. In contrast to this, R CrB runs along at sixth magnitude and in a completely random fashion will show decreases in brightness that sometimes dim the star to 15th magnitude. After the extinction episode the star returns to normal brightness. This star has been monitored for more than 150 years and no regularity has been established in its brightness fluctuations. R CrB is a carbon star, and since carbon is a refractory material Loreta (*3*) and O'Keefe (*4*) suggested that the changes in brightness could be due to the condensation of graphite clouds in the star's atmosphere. O'Keefe showed that the vapor pressure–temperature relation for carbon would allow graphite to form. Thirty-five years after the Loreta-O'Keefe suggestion a circumstellar shell was discovered (*5*). This shell, with a characteristic temperature of about 600°K, becomes evident at wavelengths longer than 2 μm, now accessible to infrared astronomers. The chemical composition of the shell is still unknown, but it is believed to be carbon or silicon carbide or a mixture of these since they are the refractory elements expected in a

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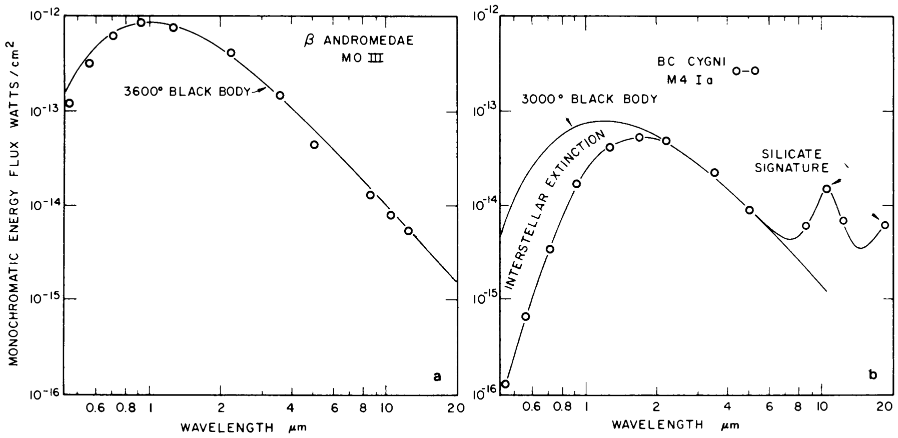
carbon-rich environment. It should be noted that the carbon-to-oxygen ratio is a very significant indicator of evolution. The sun is oxygen-rich.

Optical spectroscopists had evidence that late-type (cool) giants and supergiants inject matter by mass loss into the interstellar medium. This evidence is the doubling of many of the strong absorption lines. One component arises in the stellar reversing layer and the other presumably in a circumstellar shell. Deutsch (*6*) showed that this characteristic was common in a sample of 53 M-type giants and 8 luminous supergiants. The luminosities of the giant stars are typically 100 times the solar luminosity and those of the supergiants up to 100,000 times the solar luminosity. All of these stars are oxygen-rich. The main sequence of hydrogen-burning stars consists of oxygen-



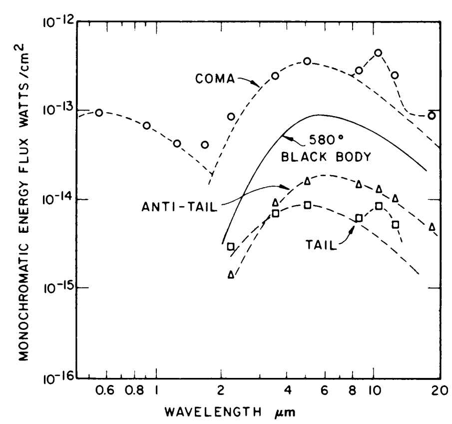


Fig. 1 (left). (a) The energy distribution of the normal giant β Andromedae closely follows that of a 3600°K blackbody. (b) The supergiant BC Cygni lies behind obscuring interstellar matter in Cygnus. The effect of the interstellar extinction is shown at short wavelengths. The excess emission at 10 and 20 μm arises in a circumstellar shell containing silicate material. Fig. 2 (right). Energy distribution of the coma, tail, and antitail of comet Kohoutek on 1.2 January 1974. In the coma the short-wavelength points arise from reflected sunlight and have the colors of a 6000°K blackbody. The long-wave fluxes come from thermal radiation by small grains and show the silicate signature. The tail has the same features. The antitail has a blackbody temperature appropriate to the distance from the sun and is composed of very much larger grains than those in the coma and tail.

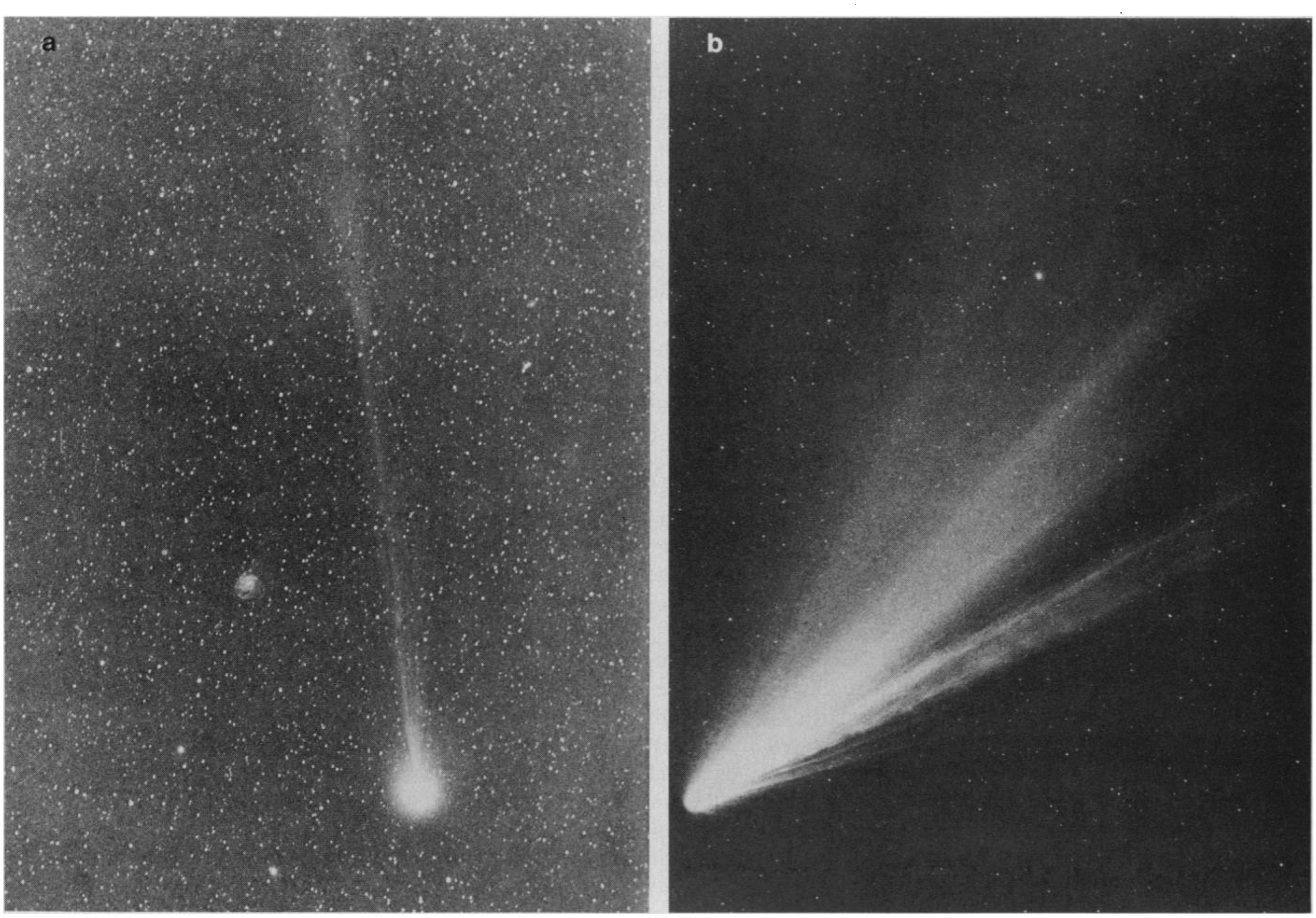


Fig. 3. (a) Comet Kobayashi-Berger-Milon on 31 July 1975. This is a type I gaseous comet tail. (b) Comet West on 7 March 1976 was an example of a comet with both type I (gassy) and type II (dusty) tails. [Photographs by James Matteson, University of California at San Diego]

rich stars which evolve after hydrogen burning to the red giants. The very luminous supergiants are a separate class of young stars. Carbon stars like R CrB are less common than oxygen-rich stars since they require nuclear processing by helium burning and represent an advanced phase of stellar evolution.

Gilman (*7*) showed by thermochemical calculations that oxygen-rich stars would be expected to condense aluminum and magnesium silicates in their atmospheres, whereas carbon stars should condense carbon and silicon carbide. The silicate materials indicated are similar to the minerals that are most abundant in the crust and mantle of the earth, the mineral olivine being one example.

Woolf and Ney (*8*) discovered a broad infrared emission feature centered at 10 μm in the energy spectra of two giants (χ Cygni and Mira) and two supergiants (α Orionis and μ Cephei). These were four of the stars in which Deutsch had detected circumstellar lines in the visible. Woolf attributed the emission band in the infrared to the stretching resonance in the Si-O bond. Subsequent observations (*9*) showed a second feature at 20 μm, believed to be due to the bending mode in the O-Si-O configuration. The emission feature in the stellar spectra observed with broadband filters matched well the absorption seen by Lyon (*10*) in optically thin rock samples. Within 2 years the "silicate signature" had been found in emission in the supergiant irregular variable stars (*11*), in the dust in the Orion nebula (*12*), and in the coma of comet Bennett (*13*). It has also been seen in absorption toward the galactic center (*14, 15*) and in the Kleinmann-Low nebula in Orion (*16*). Hanel (*17*) has detected it in the dust on Mars in emission and absorption. The martian dust storms cover the planet, and if the underlying surface is colder than the dust the feature is in emission; if the underlying surface is warmer the silicate signature is in absorption.

The opacity of silicates is very high, approaching 5000 cm^2/g at 10 μm. This means that to see the wavelength (λ) dependence of the opacity requires small grains. With an opacity of 5000 cm^2/g and a density of 1 g/cm^3, a grain becomes optically thick at a diameter of 2 μm. The existence of the signature in a cosmic source therefore requires the presence of micrometer or submicrometer grains.

In order to study the dependence of the strength of the 10-μm feature on stellar characteristics, Humphreys *et al.* (*18*) observed a group of supergiants in the Carina nebula. They showed that the feature became stronger in stars of later spectral type (cooler stars) and in stars of higher luminosity. Figure 1 shows the comparison between a late-type supergiant with high luminosity and a less luminous giant.

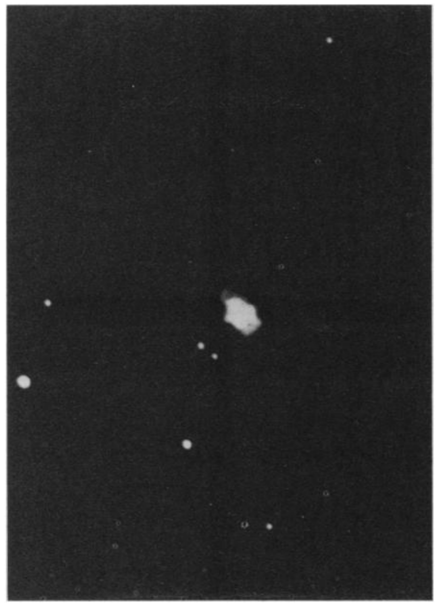


Fig. 4. The η Carinae (homunculus) nebula is the brightest known object in our galaxy at a wavelength of 10 μm. This nebula has grown from stellar dimensions in 1840 to its present diameter of about 6 arc seconds.

The long-period variable Mira stars are a very abundant kind of stellar object. Most of these are oxygen-rich and show a weak 10-μm feature. Gehrz and Woolf (*19*) considered these stars and calculated the quantity of dust injected into the galaxy by their mass loss. They concluded that the mass injected was sufficient to equal the mass removed by star deaths. Star dust seems to be a very important contributor to the mass balance of the interstellar medium.

There are several exceptions to the rule that dust shells are found around late-type stars. They fall into two classes.

First, dust is found emitting the silicate signature in regions surrounding the Orion O and B hot stars (*20*). The Orion shells are very large and cool. Their temperatures are 150° to 250°K and their optical depths are of the order of 10^{-3}. The sizes of the emitting regions are about 10,000 A.U., as opposed to several hundred astronomical units around the giant stars. It is believed that the Orion dust nebulae are heated dusty regions of the same material that condensed to form these young stars. The Trapezium stars are surrounded by one of these dust nebulae.

The second kind of silicate dust shell, which exists around a star too hot to condense refractories, is exemplified by the G star HR 5171 (*21*). Stothers (*22*) suggested that this star evolved approximately horizontally on the Hertzsprung-Russell diagram and that its dust envelope represents the fossil remains of a shell formed when the star was cooler.

Much of the exploratory work has been carried out with broadband filter systems ($\lambda/\Delta\lambda$ = 10), simply because they have better signal-to-noise ratios. However, work by Merrill (*23*) and others at ten times this resolution has failed to reveal any significant structure within the 2-μm-wide feature. Very-high-resolution observations of a few objects (*24*) show that no detail is seen even at $\lambda/\Delta\lambda$ = 1000. These studies (*25*) do show that one silicate, quartz, is ruled out because its emission spectrum peaks at 8 μm, which is far shorter than the wavelength of 9.8 μm at which the astrophysical materials peak.

Dust in Comets

The first indication that comets were bright in the infrared came with Becklin and Westphal's work on comet Ikeya (1965f) (*26*). The silicate feature was discovered in comet Bennett (1969i) (*27*). Several years elapsed before another comet bright enough to be studied in the infrared became available. Then in 2 years three bright comets appeared. Each one added some new facts to the intriguing picture.

Comet Kohoutek (1973f) was intensively studied (*28–33*). The observations showed that this comet had the silicate signature in the coma and tail, but not in the antitail or sunward spike (*28*) (Fig. 2). In addition, the dust in the coma and tail was warmer than a blackbody at the same distance from the sun. This would be expected if the particles were smaller than the infrared wavelength; that is, with diameters in the micrometer range. However, the grains could not be as small as 0.1 μm in radius because no appreciable Rayleigh scattering was evident at wavelengths of 0.5 μm. The antitail particles took on the blackbody temperature appropriate to the distance from the sun and showed no "dust bump." They were either large particles or of a different composition. Sekanina's (*34, 35*) elegant dynamical studies provided the answer. The antitail particles had to be much larger (up to 100 μm in radius) in order to follow orbits that made them appear in the appropriate position. The antitail consists of particles fragmented from the comet weeks before their observation, and these particles are in true solar orbit, capable at some future time of producing "Kohoutek shower meteors."

Comet Bradfield (1974b) (31) seemed to be almost a twin of Kohoutek in brightness and the strength of the silicate feature. However, after passing perihelion this comet lost its silicate signature and subsequently dimmed abruptly. This is interpreted as an indication of a change in the quantity or size of the emitted grains.

The comet Kobayashi-Berger-Milon (1975h) (36) was morphologically different from other comets. It had what appeared to be a dominantly gaseous tail. This comet did have dust but no silicate signature. It is tempting to speculate that this comet may have had a coma composed of larger grains like those in the antitail of Kohoutek.

Finally, comet West (1975n) had its own personality. In addition to fragmenting into four pieces near perihelion, it passed between us and the sun, allowing us to determine the scattering function of the grains. Observations at wavelengths from 0.5 to 20 μm showed increases in the intrinsic brightness as the comet fragmented, but also demonstrated a very strong forward scattering peak at short wavelengths (37). The scattering function can be well matched by dielectric grains with radii of the order of 1 μm. Metallic grains and particles smaller than 0.1 μm are ruled out.

Two additional conclusions can be drawn from the comet data. The material responsible for the 10-μm feature is very refractory, with the grains surviving at temperatures of 1000°K. The cometary albedo, observed at scattering angles near 90°, is uniformly 0.2; however, the forward scattering peak will raise this considerably when integration over all angles is carried out. The bolometric Bond albedo is at least 0.35 for the scattering function of comet West. Figure 3 shows the morphological difference between "gassy" and "dusty" comets.

Comets are believed to be the remnants of the most primitive material in the solar nebula. It is intriguing that their dust has similar characteristics to that in more remote and exotic astrophysical locations. Comets can be studied in more detail because their reflected light and thermal emission can be seen uncontaminated by the direct light of the illuminating star. In addition, a comet coma is at a fixed and known distance from the sun, whereas circumstellar dust shells contain dust particles at different distances from their stars and are by necessity observed in the presence of the direct starlight. The importance of comets in the understanding of star dust cannot be overemphasized.

Dust in Novae and Related Objects

Novae are impulsive events in which stars increase their brightness by factors of many millions and acquire luminosities as much as 500,000 times that of the sun. Novae are relatively frequent, several being detected each year in our galaxy. Only a few have been studied in the infrared, where the presence of dust can be detected. Nova Serpentis (38, 39) was one of these. This nova began as a hot blackbody and expanding shell. Thirty days after the nova explosion, a dust shell condensed. Although in principle the nova shell might "snowplow" dust in the interstellar medium, the quantity of dust in evidence was much too large to be explained this way (40). The dust shell expanded and cooled, and for some time its thermal radiation produced most of the observed luminosity. Nova Cygni 1975 was also carefully observed at the important wavelengths (41). It produced only an ionized gas shell and no dust condensation.

A pair of more venerable objects (η Carinae and RR Telescopii) classed as slow novae seem to show, respectively, the characteristics of the fast novae Serpentis and Cygni.

The object η Carinae (Fig. 4) is, without question, the most spectacular dusty infrared object. This star was observed by John Herschel at the Cape of Good Hope in 1843 when it rose from fourth magnitude to become the second brightest visual star in the sky. Subsequent determination of the distance as 2.5 kiloparsecs showed that η Carinae must have been one of the most luminous stars—if not the most luminous—in the galaxy, having a luminosity 5 million times that of the sun. After 1860 the visual brightness declined, but infrared observations in 1968 by Neugebauer and Westphal (42) showed that the object is

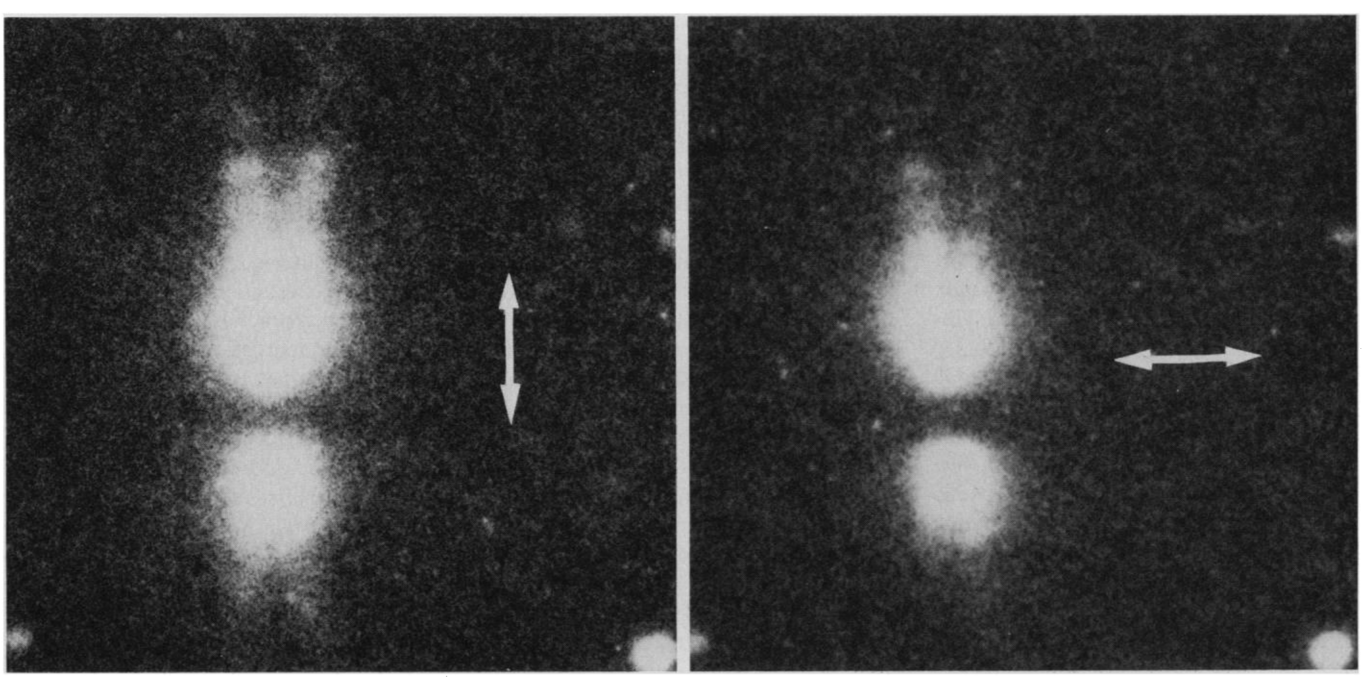


Fig. 5. The egg nebula in polarized light. These are identical exposures with crossed polarizers. The arrows show the direction of transmission of the magnetic field vector in the electromagnetic wave. [Photograph by R. Cromwell, Steward Observatory]

presently emitting as much energy as it did at maximum visual brightness, but that the energy is now in the infrared, with the energy flux peaking at about 15 μm. It is believed to be an ultraviolet star immersed in a dust cloud. Subsequent studies (*43, 44*) have shown that the dust shell has a diameter of 6 arc seconds and that the silicate signature is in evidence. In contrast to the dusty η Carinae, RR Telescopii has an ionized shell of gas like that around Nova Cygni, except that the RR Telescopii shell has remained ionized for decades (*44*).

Stars Embedded in Their Own Dust

There are two phases of stellar evolution in which stars find themselves enshrouded in dust. One of these is the birth of the stellar system, and the dust and gas from which the protostar is condensing become its cocoon. When the star ignites its nuclear furnace its luminosity will increase and blow the dust and gas away. The chance of seeing a protostar is small because during the initial collapse the star is living on gravitational energy, and during its later stages it uses nuclear energy. For the sun, the gravitational time is 10 million years and the nuclear time 10 billion years. We could only hope to find one in a thousand stars in early collapse. But when we do, they will be infrared objects surrounded by dust. The other phase in which stars may be surrounded by dust is late in life, when they have ejected dust of their own to make their shrouds.

We now know a class of infrared objects that have very thick dust shells and reradiate the stellar energy at long wavelengths. The dust shell acts as a calorimeter, and the energy distribution resembles that of a soldering iron or a planet with a blackbody temperature of 100° to 1000°K. In many cases, however, optical spectroscopists can detect the features of an underlying stellar photosphere of higher temperature appropriate to the spectral type of the embedded star. The first such object to be identified is known as NML Cygni (*45*) and it was discovered in the Caltech 2 Micron Infrared Sky Survey. Stars of this kind are sometimes called NML Cygnids or just cygnids, although the nomenclature has been criticized because meteor showers are classified by the constellation that includes their radiant. There are more than 50 known cygnids, and I use the term to indicate the class of objects in which the energy is largely radiated as by a cool blackbody—too cool to be a solar photosphere. The optical depth of the shells is greater than that found in normal giants and supergiants, and in many cases no signature of silicates or silicon carbide can be seen.

At least seven of the cygnids have nebulosity associated with them, and this nebulosity is highly polarized in the visible region of the spectrum. The morphology of these objects has led to a model, first proposed by Herbig (*46, 47*), in which a central star is surrounded by a dense disk or doughnut of dust, which absorbs much of the stellar energy and becomes the infrared source. The light of the star that shines out of the hole in the doughnut illuminates thinner clouds of dust, and the polarization is produced by scattering in the associated reflection nebulae. If the dust grains are small and the geometry is perfect, the polarization could approach 100 percent. The most extreme example is the "egg nebula" in Cygnus (Fig. 5) (*48*), whose energy distribution is shown in Fig. 6. Originally nicknamed the egg because of its nonstellar appearance on the National Geographic–Palomar Sky Survey plates, it actually consists of two visible small nebulosities separated by 7 arc seconds. Each component is polarized in the same direction and the polarization of the total visible radiation is 50 percent (*48, 49*). Indeed, the polarization is so great that it was discovered by S. R. B. Cooke [see (*48*)], using a 12½-inch reflector and observing in a bright sky with a quarter-moon. Some parts of the object are almost completely polarized. The light from the nebulae shows the spectrum of the central star, which seems to be an F-type supergiant (*50*). The infrared source radiates 1000 times the energy in the reflection nebulae and is midway between them, as shown by scans with the 200-inch telescope (*51*). The central dust doughnut is so thick that not a trace of visible light can be seen at the position of the central star. It is now known that this object is a strong molecular source at radio wavelengths (*52, 53*) and that it has increased in visual brightness by a factor of 4 in the last 50 years (*54*). Two explanations have been advanced. The first is that the dust torus could be material orbiting the star and destined to form planets. The reflection nebulae in this model resemble the Oort cloud of comets in the solar system. Others believe that the system represents a stage in the formation of a planetary nebula (*52, 53*). Whichever is correct, further study of systems like this should reveal new facets of stellar evolution and may give information about the formation of stellar geometries resembling our solar system.

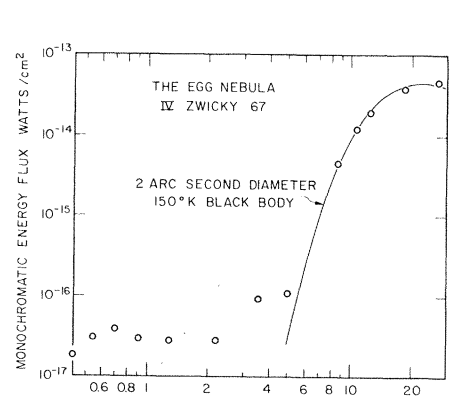


Fig. 6. Energy distribution of the egg nebula. At short wavelengths the polarized scattered light from the reflection nebulae contains only 1/1000 of the energy radiated by the optically invisible infrared source located between the nebulae in Fig. 5.

Solar System Analogs of the Astrophysical Dust

Laboratory measurements of the absorption spectra of many minerals reveal differences in the silicate signature between 8 and 14 μm. For example, quartz has a peak at too short a wavelength, and anorthosite has a double peak not seen in the astrophysical sources. The high abundance and great variety of silicates in the earth, moon, and meteorites make the search for analogs a challenging "astrogeological" problem.

Rose (*55*) has examined a large group of materials including terrestrial minerals, lunar soils, meteorites, and slags from ancient smelters. He has been able to study both the emission and absorption spectra with particles of known sizes. He finds a definite class of materials that closely imitate the astrophysical signature. Day (*56*) has made artificial silicates chemically and has demonstrated that a precipitated amorphous magnesium silicate gives a different spectrum than the same material which has been heated and crystallized. The work of Rose and Day will certainly contribute to our understanding of the environment in which the cosmic star dust is formed.

Could our sun produce dust? The models that have successfully predicted the characteristics of the shells around luminous cool stars would appear to rule out the sun as a grain producer. However, tiny quantities of very refractory materials might be made. Hemmenway and his collaborators (*57*) have reported finding particulate matter in the noctilucent clouds sampled by rockets, and they suggest that the dust is of solar origin. The zodiacal cloud does consist of solar system dust, but it is generally believed to be injected by comets and asteroidal debris. In any event, the total mass of dust in the solar system is of the order of 10^{-17} the mass of the sun, whereas a supergiant M star might have 10^{-7} solar mass of silicates in its shell.

Summary

Infrared astronomy has shown that certain classes of stars are abundant producers of refractory grains, which condense in their atmospheres and are blown into interstellar space by the radiation pressure of these stars. Metallic silicates of the kind that produce terrestrial planets are injected by the oxygen-rich stars and carbon and its refractories by carbon stars. Much of the interstellar dust may be produced by this mechanism. A number of "infrared stars" are completely surrounded by their own dust, and a few of these exhibit a unique morphology that suggests the formation of a planetary system or a stage in the evolution of a planetary nebula. Certain novae also condense grains, which are blown out in their shells.

In our own solar system, comets are found to contain the same silicates that are present elsewhere in the galaxy, suggesting that these constituents were present in the primeval solar nebula.

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Mathematics Underlying the Rate-Dependency Hypothesis

The mathematics of rate-dependency interpretations of the effects of drugs on behavior are examined.

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The sensitivity of operant behavior (behavior controlled by its past consequences) to drugs acting on the central nervous system was demonstrated in laboratory experiments nearly four decades ago (*1*), yet the impetus for the use of experimentally controlled operant behavior as a tool in behavioral pharmacology came in the 1950's, when Dews undertook a systematic analysis of the behavioral effects of drugs, using the procedures developed by Skinner (*2*) to study operant behavior. Dews performed his experiments on food-deprived pigeons trained to peck a small plastic disk to obtain temporary access to grain (*3*). A microswitch behind the disk was operated by each peck, providing an objective measure of pecking responses. Food presentation—that is, access to grain—was dependent on the pigeons' responding and occurred intermittently in accordance with one or more rules, commonly called schedules, which were programmed by means of electronic equipment. Under a fixed-ratio schedule, for example, every *n*th response was immediately followed by food presentation; under a fixed-interval schedule, the first response occurring after a fixed time had elapsed was followed by food presentation. These and other schedules of reinforcement maintained characteristic patterns of responding that were consistent and reproducible across sessions and subjects, and provided stable baselines for studying the effects of drugs (*4*).

Initially, reports by Dews and other investigators describing the effects of drugs on schedule-controlled operant behavior emphasized the role of the schedule, the distinctive stimuli associated

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