FROM INTERSTELLAR DUST TO COMETS TO THE ZODIACAL LIGHT

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Abstract. We consider the consequences of the assumption that the interplanetary particles which produce the zodiacal light have evolved from interstellar dust via comets. The chemical evolution of interstellar dust followed by the process of aggregation into the cometary nucleus and the subsequent ejection of cometary debris provide the basis for a model for the interplanetary particles. The scattering properties of these particles are reasonably consistent with current observations of the variation with elongation angle of the brightness and polarization of the zodiacal light. The major chemical constituents of the model are in the form of a matrix of volatile ices and complex nonvolatile molecules containing C, N and O in which are imbedded silicate and metallic inclusions.

1. Introduction

According to the mechanisms proposed by Cameron (1973), Goldreich and Ward (1973), Safranov (1972), and Biermann and Michel (1978) for the accretion of cometary nuclei in the outer parts of the presolar nubula or in associated cloud condensations we are led to the presumption that comets are made of aggregated interstellar dust. Thus both the chemical and physical properties of the comet nuclei are given by some derivative of the basic chemical and physical characteristics of the interstellar dust.

First Whipple (see Whipple 1978 in "Cosmic Dust"), and subsequently others have, suggested that comets are a source of the interplanetary particles. If this is correct and, if the particles are then small (but not too small according to the work of Giese et al. (1976) and Fechtig (1976)) clumps of primordial interstellar dust, we are led to certain models for the zodiacal light particles and can then consider the optical and scattering properties of such particles.
We consider this in three steps:

a. The physical and chemical description of cometary material as aggregated interstellar dust.
b. The nature of cometary debris and possible modifications in the solar system.

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c. The scattering properties of the cometary debris.

2. Initial Cometary Material

A general picture of the interstellar dust (see Greenberg 1978 in "Cosmic Dust") which matches the astronomical observations is that it consists of essentially two components: a) Elongated core mantle particles of overall dimension ∿ 0.3 μm thickness the cores consisting of a silicate (or metallic oxide) type material of ∿ 0.1 μm thickness and the surrounding mantles consisting of the ultraviolet processed ices (molecules with predominantly O, C, N and H); and b) Bare refractory particles of size $\lesssim$ 0.01 μm constituting a small fraction by volume of the total interstellar dust. The maximum size attainable for the mantles by accretion in the interstellar medium but with no coagulation is ∿ 0.4 μm thick. Laboratory investigations are being made at the Astrophysics Laboratory at the University of Leiden of chemical processing of analog materials of interstellar ices at low temperatures (∿ 10 K) and the resulting chemical and physical composition (Hagen et al. 1979). Astronomical observations in the infrared have been interpreted in terms of results of some of our experiments which confirm the existence of complex mantle materials (Allamandola et al. 1979a).

We have created many molecules by irradiation of a roughly cosmic abundance (by elements) mixture of simple molecules like H_2O, CH_4, NH_3, CO deposited on a substrate at 10 K. We have also created molecules containing only O, C and N (no metals or silicon were used in our first samples) which are so complex that they are not melted or evaporated at 300^o C (600 K)! We have found these existing as a residual yellow powder on the cold finger in our cryostat after irradiation by ultraviolet. Under somewhat different conditions we have produced on several occasions a yellow viscous liquid. For one of these a mass number 514 was measured in the mass spectrometer. On yet another occasion a brownish residue was left after warm-up. The liquid evaporates at between 400 K and 500 K. The yellow powder molecule may well have a molecular weight in the thousands. The infrared absorption spectrum of the yellow liquid is characteristic of amides and perhaps some ring structures. It is soluble in water. There is strong evidence that the large molecules produced within the analog interstellar grain material are typical of pre-biotic material.

In the final stage before comet formation (Greenberg, 1979) it is most likely that the dust mantles contain all (certainly most of) the available condensible material resulting from combinations of O, C, N and, of course, whatever Fe, Mg, Si, Ca etc. have been left over in the gas. These latter can make only a very small relative contribution to the mantles since most of them are already bound in the refractory core and bare particle materials. Actually the bare particles could contain in their population pieces of the nonvoltile residues of photoprocessed grain materials (Greenberg, 1974). In addition it is likely that, as a result of turbulence in the pre-solar nebula, the man-

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tles have also accreted the bare particles because the interparticle speeds in a turbulent molecular cloud are $\sim$ 2 km s^{-1}; i.e. the collision rates of the bare particles with each other and with the core-mantle particles exceed Brownian motion speeds by 10^4 to 10^5 (Greenberg, 1979a).

The primordial composition of the comet is then suggested to be in the form of a melange of all sorts of molecules resulting from the photochemically processed ices and accreted interstellar gas in which are dispersed the bare particles ($\sim$ 5% of the total volume). Embedded within this matrix would be the needle-like (elongations $\gtrsim$ 2) silicate cores spaced according to the manner and form in which the grains have finally aggregated; namely, separated, in the mean, by the order of the thickness of the mantles. The cores constitute another $\sim$ 5% of the volume so that about 90% of the comet nucleus consists of the modified ices.

If the comet nucleus is not only formed cold but remains cold after storage in the Oort cloud (1950) for the 4.5 billion years since formation, we would now be seeing the comet nucleus in its pristine form. Among the obvious processes which might modify its composition and physical character are: (1) Heating by residual radioactivity, (2) Bombardment by cosmic rays and other energetic radiation. Although the latter could modify the surface of the comet nucleus the penetration depth is rather small. The former has been shown by Lewis (1971), who considered heating by primordial ^{40}K alone, to provide a temperature rise in the center of a 10 km comet nucleus which is certainly less than 10 K. If one includes ^{26}Al the temperature is substantially higher in the beginning but it still does not appear to provide the basis for very large chemical differentiation except at the very center.

We note here that the model of the comet nucleus proposed here (Greenberg, 1977) differs from that of other "icy" models in the relative proportions of volatile to nonvolatile C, N, O compounds and the fraction of rocky or metallic material (see e.g. Donn, 1963). The comet density we arrive at for a fairly compact comet nucleus material including the cores of the core-mantle interstellar grains is about 1 gm cm^{-3} as had been suggested by Whipple.

3. Cometary Debris

In the course of being subjected to nongravitational forces as it approaches the sun, the comet sheds pieces off its surface. The structure of this debris must consist, at least in part, of the primordial comet nucleus matrix material with embedded silicate needles. Some of this matrix material is volatile. Thus once a small piece of the comet (consider sizes from 10^{-3} to 10^{-1} cm or larger) is exposed further to the solar wind and radiation, the volatile molecules near the surface may be "eroded" away leaving a tangled structure of the silicate cores tenuously bonded by some remaining less volatile mantle material. Current theories for such erosion by the solar wind lead to an erosion rate of H_2O ice of about 0.1 Å per year at 1 a.u. (Lanzerotti et al.

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1978). If a comet particle has a mean lifetime of the order of 10^5 years in the solar system its outer layers will be pitted to a depth of about 1 μm. The particle appearance would then, from the outside, bear some resemblance to a bird's nest. Continued erosion of the particle will further release the refractory particles so that the small interstellar dust core silicate particles can also constitute some portion of the solid particles in the interplanetary medium. This highly simplified scheme must be subjected to more quantitative investigation. There does not seem to be any simple way to understand how the particles we picture can evolve into particles of the type collected in the earth's atmosphere (Brownlee, 1979) or the particles which produce the lunar cratering statistics as interpreted by Le Sergeant and Lamy (1978). It would appear necessary to go back to a reconsideration of the parent body from which such particles come in order to obtain such particles.

We now make a jump to consideration of the scattering properties of the interplanetary particles as we picture them to see whether they are at least consistent with the observations of the zodiacal light.

4. Scattering Properties of Cometary Debris

The scattering by complex particles is not readily subjected to normal theoretical approaches. It can however be approached experimentally by the microwave analog method (see Greenberg, 1974b for some references). There is currently a program of experiments being performed by Mr. Bo Gustafson at the Microwave Scattering Facility at the Space Astronomy Laboratory in Albany to study the brightness and polarization produced by what we call bird's nest particles (Greenberg and Gustafson, 1978). We have modelled the analog cometary debris particle out of a tangle of lucite rods whose index of refraction at 3 cm is very like the silicate index of refraction in the visible and whose size relative to the wavelength is roughly comparable to the silicate core size relative to visible radiation (actually 6700 Å). The overall ensemble particle sizes have been limited (partly for ease of construction) to ones which scale to interplanetary particles several times 10^{-4} cm. This is somewhat smaller than the particle sizes which may be dominant but there is a strong suggestion that the bird's nest type particle does not change its qualitative scattering characteristics with increasing ensemble size. At this time we have obtained results which are consistent with the observations and which give substantial indication of producing as good a match with the polarization and brightness variation with elongation as the very different type of irregular type particles considered by Giese et al. (1978).

The particles whose scattering properties we present in Figures 1 and 2 consist of randomly aligned 0.48 cm diameter cylinders of lucite ($m = 1.61$) with elongations respectively of 1:1, 2:1 and 4:1 all in roughly spherical ensembles. On each particle the total volume of inclusions is approximately the same; i.e. 534x1:1, 240x2:1 and 125x4:1 cylinders. For convenience in those preliminary experiments we have

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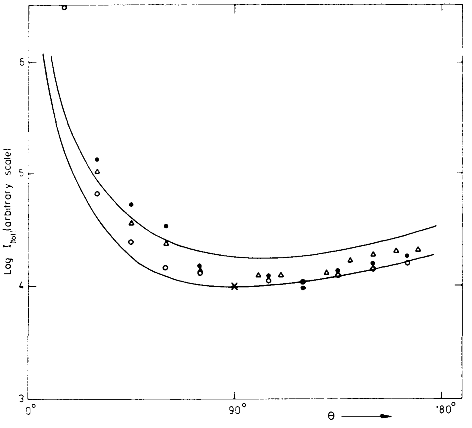

Figure 1. Brightness vs. scattering angle for various ensembles of thin cylinders. All curves normalized to same value at θ = 90°. Solid curves give range of observations (from Giese et al. 1978), dots = 1:1, triangles = 2:1, circles = 4:1.

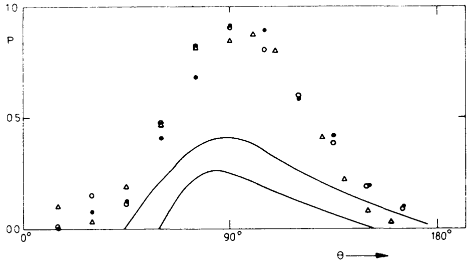

Figure 2. Polarization vs. scattering angle for various ensembles of thin cylinders. Solid curves give range of observations (from Giese et al. 1978), dots = 1:1, triangles = 2:1, circles = 4:1.

used a very low index of refraction matrix material (m−1 << 1) rather than one resembling the ices in its optical properties (m ≃ 1.3). Future experiments are planned with models using dylite plastic (m ≃ 1.3) as a more realistic optical representation of the matrix. Since the surfaces of the real interplanetary particles are presumed to be very porous we believe that what is shown in Figures 1 and 2 is at least a good preliminary indication of what to expect. We see that the total scattering intensity is well matched. Although the shape of the polarization curve is quite good the absolute polarization is substantially higher than observed (also a property of most of the particles of Giese et al.) but we expect that filling in the matrix will bring this down to a reasonable level.

In any case it appears that one can produce equivalent curves of brightness and polarization with both the nonabsorbing very tenuous particles considered here and the much denser absorbing particles considered by Giese et al.

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5. Concluding remarks

Although we have shown that particles consisting of a random ensemble of coagulated interstellar grains appear to provide a reasonable basis for explaining the brightness and polarization of the zodiacal light, much further work is required to show whether or not they are unique and how they may be related to current theories and observations of particles in the solar system. It appears necessary to reexamine the theories of thermal and chemical evolution of comets as well as the zodiacal light particles.

Based on the model proposed here one is led to search for: (1) Very complex organic molecules in comets and zodiacal light particles, (2) Changes in structure of comet dust far away from the nucleus particularly in terms of observing increasing numbers of small silicate particles where conditions of substantial erosion or evaporation occur.

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Hawkes: You have synthesized amino subgroups. Do you consider it possible that further processing could lead to the development of life forms?
Greenberg: The large molecules we make certainly seem to be of a prebiological nature. But if and how they could eventually be precursors of living matter is something about which I can only speculate. I infer that the total amount of such large molecules in space is very large but whether there exists an opportunity for it to find the right environment for further evolution I have no idea.

ReVelle: You mentioned that there were problems with the scaling of gas pressure in your simulation system. How does this affect your results, especially the time scale associated with the processes involved?
Greenberg: The gas pressure in the system is too small to affect the processing of the layer of frozen deposited material.

Lokanadham: Can one draw any conclusion about the origin of comets from the chemical composition of interstellar grains?
Greenberg: One can hope to infer the chemical composition of comets from theories of the chemical composition of interstellar grains but not the reverse. However, from the chemical composition of the comet we should be able eventually to derive the chemical composition of those interplanetary particles which originate in comets.

Roach: If the particles are primordial, shouldn't they represent third (or later) generation post primordial?
Greenberg: The particles represent a sample of the interstellar material out of which the solar system was formed. They are therefore no more or no less primordial than the presolar nebula.

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Hill: How old are the comets? Once material forms into a comet, is it long lived in that form?

Greenberg: The comets were formed at the birth of the Solar System so they are as old as that. Those comets which make up the Oort cloud have remained in the same form they had at birth because they are far from any source of processing except perhaps some surface effects by high energy photons including xrays.

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