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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Origin of Dust in the Solar System [and Discussion]

S. V. M. Clube, M. A. Saunders, J. Darius, Bernard Lovell, F. L. Whipple and E. Anders

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The origin of dust in the Solar System

By S. V. M. Clube
Department of Astrophysics, South Parks Road, Oxford OX1 3RQ, U.K.

The assumption that the Zodiacal Cloud is a predominantly meteoritic rather than a meteoroidal complex is questioned. On the basis of (i) the observed exposure ages of interplanetary dust particles collected from the stratosphere, (ii) the compressive strength of the commonest fireballs, (iii) the existence of a broad ecliptic stream centred on the Taurids and (iv) the observation of substantial short-lived meteoroid swarms therein, a suitably consistent replenishment model is constructed in which the Zodiacal Cloud appears to derive from a now defunct large comet that arrived in an Earth-crossing orbit *ca.* 10–100 ka ago. A corollary of this model is that the latter's remnant, a surviving large meteoroid, may be reactivated as a comet at intervals of *ca.* 1 ka giving rise to a variety of observable effects such as Zodiacal Cloud enhancements and rare multiple bombardments of the Earth by many bodies with masses at least 10^{11} g, which typify a general process throughout Earth history responsible for climatic excursions and extinction events. It is recommended that a search be conducted for the large meteoroid or minor planet responsible for the dust now in the Solar System, to place our understanding of the latter's evolution on a secure quantitative basis. If verified, this model would have profound implications so far as our understanding of the origin of comets is concerned because most of the cometary mass would apparently be contained in large differentiated bodies.

1. Modelling the interplanetary dust complex

The Zodiacal Cloud is now generally taken to be a *meteoritic* complex in which typical fireball progenitors of mass up to 10^3 g (density *ca.* 2.5 g cm^{-3}, albedo *ca.* 0.1 and compressive strength similar to that of basalt) are degraded by catastrophic collisions and lost from the Solar System in the form of micrometeorite particles through the combined effects of Poynting–Robertson drag (chiefly in the mass range $10^{-9} \leqslant m \leqslant 10^{-3}$ g) and solar radiation pressure (in the range $10^{-18} \leqslant m \leqslant 10^{-12}$ g) (Grun *et al.* 1986; cf. Dohnanyi 1978; Le Sergeant & Lamy 1980; Leinert *et al.* 1983). But for this picture to be acceptable, it is also necessary that it be consistent with recent *in situ* measurements of the interplanetary dust concentration (Zook & Berg 1975; Hoffmann *et al.* 1975; McDonnell 1978; Grun *et al.* 1980) and the long-term microcratering flux recorded by the Moon (Fechtig *et al.* 1975; Morrison & Clanton 1979). According to the recent calculations by Grun *et al.* (1986), this combination of constraints allied to brightness measurements of the Zodiacal Cloud cannot be met with a simple steady-state model. They therefore suggest that the concentration of low-mass particles in the range $10^{-9} \leqslant m \leqslant 10^{-3}$ g may be growing on a timescale of *ca.* 100 ka and that the excess microcratering on the Moon by particles of less than 10^{-12} g might be understood in terms of the effects of secondary cratering due to oblique-angle hypervelocity impacts. They also point out, however, that the material involved may not be wholly similar to basalt; thus it is possible that a substantial fraction of the net flux through the meteoritic complex comprises porous *meteoroidal* material of lower density and much lower compressive strength, and that this material is intermittently replenished on timescales very much shorter than 100 ka. Current *in situ* measurements of the interplanetary dust concentration (β-meteoroids, radio meteors and photographic meteors) would then be close to the long-term background flux whereas the integrated cratering and microcratering flux on the Moon would reflect more the occasional rapid throughputs of much larger amounts of material from the mostly very weak bodies whose mass distribution corresponds to that observed for the larger fireballs ($10^3 < m < 10^8$ g (McCrosky 1968)):

$$\mathrm{d}n\,(m+\mathrm{d}m, m) \propto m^{-\alpha}\,\mathrm{d}m; \quad \alpha = 1.67. \tag{1}$$

If such bodies are a factor of *ca.* 10^2–10^3 weaker than basalt (*cf.* Wetherill & ReVelle 1982), the current growth of the Zodiacal Cloud then implies a substantial fragmentation *ca.* 1 ka ago.

This picture is broadly consistent with measurements of the iridium and osmium content of deep-sea sediments (Barker & Anders 1968) and of trace elements on the lunar surface (Anders *et al.* 1973). Thus, these indicate that the accretion rate of meteoritic and meteoroidal matter on Earth is spasmodic and may reach *ca.* 100 kt a^{-1} for periods of *ca.* 100 ka, including the most recent, some two orders of magnitude greater than the underlying background flux of *ca.* 1 kt a^{-1}. Such values bracket the current annual terrestrial infall rate of *ca.* 10 kt a^{-1} (Grun *et al.* 1986; *cf.* Naumann 1966; Zook *et al.* 1970; Hughes 1978) and it seems likely that the enhancements in the terrestrial influx may therefore be due to the intermittent break-up of single large bodies whose fragmentation products are effectively suspended in the Zodiacal Cloud for periods of up to 100 ka (Barker & Anders 1968). To calculate the approximate size of the bodies responsible for such episodic infall, we assume a prefragmentation density $\rho \sim 0.1$–$1\ \mathrm{g\ cm^{-3}}$ and a radius R. Taking the Zodiacal Cloud volume to be $V \sim 10^{41}\ \mathrm{cm^3}$, the rate $\dot{Q}$ at which material is collected by the Earth (radius R_E) during periods of increased infall (incident velocity $u \sim 5\ \mathrm{km\ s^{-1}}$, say), is given by $\dot{Q} \sim \pi R_\mathrm{E}^2\, u\, \frac{4}{3}\pi R^3 \rho V^{-1}$ whence it follows that $R \sim 100$ km. With meteoroidal material *ca.* 10^2–10^3 weaker than basalt, each episode of *ca.* 100 ka then corresponds to a sequence of (tinted) Zodiacal Cloud enhancements as separate fragments of the parent body undergo degradation over periods of *ca.* 0.1–1 ka. According to this picture, the Zodiacal Cloud is sustained by successive very large *meteoroids* at intervals of *ca.* 100 ka to 10 Ma interspersed with less frequent but very large *meteorites* at intervals of *ca.* 10 Ma to 1 Ga consistent with the observation (Anders 1971) that most meteorite finds on the Earth due to falls during the past gigayear are derived from a limited number (*ca.* 10) of large parent bodies. It is implicit moreover that the Zodiacal Cloud is now fed by a very large meteoroidal body.

To be specific, it is assumed that this large meteoroid belongs to the family of very low albedo, red-black bodies (D-class asteroids), which includes 'the Trojan asteroids, Hidalgo, Chiron, comets and several small, dark outer satellites' and which contains 'kerogen-like, low-temperature carbonaceous condensates' (Hartmann 1986). The proposed body is thus looked upon as one of the most primitive objects in the Solar System, while its presumed evolution through a cometary phase into very friable, dust-inducing meteoroids is consistent with a primordial state comprising a very porous refractory matrix whose interstices are filled with a volatile carbonaceous medium. The systematic elimination of this medium from meteoroidal particles in the solar vicinity, leaving fluffy chondritic aggregates, implies that Zodiacal-Light particles are likely to be physically similar to C-type asteroidal regoliths (cf. Lumme & Bowell 1985).

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2. Modelling the source of the dust complex

Because the rate at which long-period comets are deflected into short-period orbits is *ca.* 1 ma^{-1} (Everhart 1972) and because $\int \phi(m \geqslant 10^{21}\text{ g})\,\mathrm{d}m / \int \phi(m)\,\mathrm{d}m \sim 10^{-3}$ based on the observed mass function $\phi(m)$ of comets (see, for example, Hughes & Daniels 1982), it follows that the current arrival rate of 'giant comets' with $m \geqslant 10^{21}$ g is *ca.* 1 Ma^{-1}. Giant comets may therefore plausibly be thought of as identical to large meteoroids ($R \sim 100$ km), the most recent having arrived in the inner Solar System up to 100 ka ago. A significant corollary of this hypothesis is that the otherwise enigmatic overabundance of short-period comets (see, for example, Fernandez & Ip 1983) based on the above deflection rate and lifetime of short-period comets (i.e. *ca.* 1–10 ka), may be due to the early break-up of this most recent giant comet and the dispersal of many of its cometary fragments during or after its arrival in a sub-jovian orbit. If so, the giant comet and many other cometary fragments would be expected to have evolved by now into a variety of undetected meteoroids in Earth-crossing subjovian orbits (Apollo asteroids and potential fireballs). The hypothesis thus implies that a now defunct giant comet in an Encke-type orbit is responsible for the present Zodiacal Cloud, a suggestion that has already been made by several authors e.g. Whipple (1967), Delsemme (1976) and Kresak (1980). For overall consistency, however, the spasmodic input of meteoroidal material must correspond to a long-term giant-comet arrival rate of $10^{-1}\ \text{Ma}^{-1}$ implying that comets probably reach us in episodes or showers, the latest of which may be active now (cf. Clube & Napier 1984; 1986*a*).

According to this picture therefore, the interplanetary dust complex may be in one of several different states (see table 1) depending on the epoch and duration of observation. It is implicit

Table 1. Characteristic rates of accretion of meteoroidal material by the Earth during various states of the interplanetary dust complex

state of interplanetary dust complex	average over Solar System life time	comet shower	disintegrating giant meteoroid	inactive period during disintegration
duration/a	$\sim 3 \times 10^9$	$\sim 3 \times 10^6$	$\sim 10^5$	$\lesssim 10^3$
flux/(kt a^{-1})	~ 1	$\sim 10^2$	$\sim 10^2$	$\geqslant 1$

that the Zodiacal Cloud will frequently be enhanced above a certain base level but, in general, we may expect the mass spectrum of the interplanetary dust complex to divide, as at present, into three principal régimes corresponding to β-meteoroids, meteors and fireballs. Each régime is characterized by an approximately constant mass distribution index (α_r, α_{cc}, α_e) determined by the dominant process of mass depletion (radiation pressure, catastrophic collisions, erosive collisions). The current near-Earth state of the complex has α_r $(m \leqslant 10^{-9}\text{ g}) \sim 1.5$, α_{cc} $(10^{-9}\text{ g} \leqslant m \leqslant m') \sim 2.2$, α_e $(m' \leqslant m \leqslant m'') \sim 1.67$ where $\{m', n(m')\} \sim \{10^2\text{ g}, 10^{-28}\text{ cm}^{-3}\}$. The observed $n(m)$ is therefore not in equilibrium (Dohnanyi 1978), values in the fireball régime in particular being greater than the time-averaged lunar cratering flux. This could be due to the recent fragmentation of a large meteoroid of unknown mass, but because large meteoroids are rare, and we are unable to observe them directly, it is not possible to specify the upper limit m''. Nevertheless, the observed fireball spectrum $n(m \geqslant 10^2\text{ g})$ defines one section of the present 'base level' of the Zodiacal Cloud, the rest being normalized to m' which fluctuates in response to the above depletion processes and the random disintegration of large meteoroids. It follows that the lowest base level (i.e. $m' \sim 10$ g) corresponds to a total terrestrial influx of *ca.* 1 kt a^{-1}, whereas the current level (i.e. $m' = 10^2$ g) corresponds to *ca.* 10 kt a^{-1}.

Because a very large body of mass $m'' \sim 10^{21}$ g (i.e. $R \sim 100$ km), comprising weak meteoroidal material of the postulated kind, may be catastrophically destroyed by an incident total mass Σm where $\Sigma m \geqslant (10^4\,\Gamma)^{-1}\,m''$ and $\Gamma \sim 10^6$ (cf. table IV in Grun *et al.* 1986), a single encounter with a missile of *ca.* 10^{11} g may serve to reduce it substantially to dust. Such an encounter with a typical Tunguska missile might take place within *ca.* 100 ka but partial erosion can also be expected on this timescale through encounters with bodies greater than *ca.* 10^3 g, the limit for observed fireballs above which the effect of erosive collisions becomes dominant over catastrophic collisions. Thus, for complete destruction within 100 ka by erosion, encounters by bodies of at least 10^3 g would have to occur at the rate $\nu \sim 10 \times (10^{11}/10^3)^{\alpha-1}$ Ma^{-1}, giving an equivalent lunar encounter rate of *ca.* 500 a^{-1}, in tolerably close agreement with the observed rate during 1971–6 (Dorman *et al.* 1978). It follows that the background flux of weak meteoroidal material entering and leaving the Zodiacal Cloud annually owing to encounters with a hypothetical large body would be *ca.* $f_1 f_2\, 10^3\, (10^4\Gamma)\, \nu$ g, where the factors f_i (a few) allow for the mass spectrum of the target material ($10^3 \leqslant m \leqslant 10^{21}$ g) and that of the eroding material ($m \leqslant 10^3$ g) respectively. A total influx of *ca.* 10^{14} g a^{-1} is thus implied, consistent with the observationally constrained Zodiacal Cloud outflow given by Grun *et al.* (1986). Superimposed on this fairly regular background flux, however, is the more intermittent but larger flux due to erosive encounters by bodies greater than 10^3 g. Over intervals of *ca.* 10^3–10^5 years, these enhancements produce a significantly greater average flux, *ca.* 10^{16} g a^{-1}.

In principle therefore, the scheme put forward by Barker & Anders (1968) is capable of providing a simple, self-consistent explanation of the interplanetary dust complex, but for it to work, a substantial portion of the micrometeoroid complex must be at least a factor of 10^{-4} weaker than basalt, with an age of 10 a–100 ka. There is also an expectation of discrete replenishment events of *ca.* 10^{15}–10^{17} g $(10\ \mathrm{a})^{-1}$ sustaining the Zodiacal Cloud. The question arises, therefore, whether there is any independent evidence relating to the strength and age of the meteoroidal complex, and whether replenishment events of the predicted kind take place. These separate issues will be considered in §§3 and 4, respectively.

3. Dispersed meteoroids and interplanetary dust

From the systematic observation of fireballs, it is known that most of their progenitors ($10^2 \leqslant m \leqslant 10^6$ g) are in a variety of subjovian Earth-crossing orbits similar to those of many Apollo–Amor asteroids. Although some proportion of the Apollo–Amor asteroids may originate from the asteroid belt (Wetherill 1974), many of them are probably cometary disintegration products (see, for example, Wasson & Wetherill 1979). Most fireballs thus derive from comets through an asteroidal phase, a view that has now gained further support from new asteroid discoveries (see, for example, Rickman 1985), which indicate, with due allowance for the overall discovery rate of Earth-crossing asteroids (see, for example, Shoemaker *et al.* 1979), that the short-period comets may be accompanied by as many asteroids with similar orbital parameters.

A few fireballs have been associated with known meteorite falls, however (Ceplecha 1961; McCrosky *et al.* 1971; Halliday *et al.* 1981), and a study of intermediate strength fireballs from transjovian orbits (Wetherill & ReVelle 1982; *cf.* Ceplecha & McCrosky 1976) has shown that their peak dynamic pressures take up a continuum of values in the range *ca.* 10^4–10^6 Pa. Laboratory measurements of the compressive strength of meteorites (*ca.* 10^6–10^8 Pa; Buddhue 1942) give average values that are evidently an order of magnitude above the strongest fireballs in this continuum. The commonest fireballs on the other hand, which are often too brief to be well observed, have compressive strengths that are probably an order of magnitude below the weakest in the continuum. It follows that fireballs reveal a broad range of compressive strengths lying between extremes for stones and meteoroids, which are on the order of and 10^{-4}–10^{-3} weaker than basalt respectively. Ablation studies indicate that for a given mass, the former decelerate more slowly and penetrate further into the atmosphere as a single body by reason of their robust composition, whereas the latter are mostly friable, low-density objects whose visible flight through the atmosphere terminates abruptly at high altitude as the meteoroid fragments into many small pieces. The overall picture that emerges is thus of a fireball population fed by two separate but merging sources, cometary asteroids and meteorites, the former more copious than the latter, which probably arrive in Earth-crossing orbits by similar routes, namely through successive jovian deflections and the subsequent action of non-gravitational forces (Kresak 1980).

The existence of meteoroids in the same mass range $10^2 \leqslant m \leqslant 10^6$ g is also inferred from observations outside the upper atmosphere, through near coincidence between otherwise randomly distributed small particles ($10^{-16} \leqslant m \leqslant 10^{-8}$ g) registered by *in situ* detectors (Fechtig 1982). The parent meteoroids are evidently very weakly bound because they undergo electrostatic fragmentation within the auroral plasma region. They also represent some 30% of the total flux of material flowing through the region and evidently correspond to the low mass end of the eroded meteoroid population. The physical similarities between the coincident and random groups indicate moreover that these parent meteoroids are the likely intermediaries feeding the interplanetary dust. The individual dust particles in the range $10^{-16} \leqslant m \leqslant 10^{-8}$ g differ among themselves, however, as judged by their cratering properties and hence their compressive strength, some 25% being of very low density up to 1 g cm^{-3} and probably very porous.

A rather similar distinction emerges among particles in the intermediate mass range $10^{-6} \leqslant m \leqslant 10^2$ g, especially between meteor streams which self-evidently derive from different cometary or asteroidal sources. Thus brighter meteors at appropriate pre-entry velocities are due to relatively compact single particles, whereas fainter meteors are thought to be due to very porous, fragile structures, which disintegrate into separately ablating smaller grains (Jacchia 1955). More specifically, given their common spectroscopic characteristics, the latter may be pictured as open assemblies of chondritic grains ($m \geqslant 10^{-6}$ g) held together by a lower melting point 'glue' (Hawkes & Jones 1975; Beech 1984). Indeed, it is clear that the ablation of both meteor dust particles and their larger meteoroidal counterparts responsible for fireballs, probably involves the removal of this less refractory 'glue' by heating and melting, thereby causing the parent body in each case to completely fragment.

Microparticle, meteor and fireball observations thus indicate a common meteoroidal material that comprises a skeleton of finely grained refractory substances (melting points *ca.* 500–2000 K), whose differing bulk densities imply varying degrees of porosity. These variations in structure can tell us something about the cometary material from which meteoroidal material derives. Thus, if the primordial structure has been relatively unaltered, differing concentrations

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of the volatile component may be implied; this might suggest various degrees of differentiation in cometary material, possibly consistent with an origin from a much larger body. On the other hand, the structure may reflect subsequent processing in the vicinity of the Sun: various modes of crust formation may be implied. The porosity thus remains an ambiguous factor so far as the formation and evolution of comets are concerned; however, the skeletal structure is no longer in doubt since it has also been observed in small samples of interplanetary dust collected from the stratosphere.

The masses of stratospheric particles are commonly in the range $10^{-12} \leqslant m \leqslant 10^{-9}$ g and apart from the *ca.* 5% of irregular and spherical chondritic grains that may have a predominantly meteoritic origin, most of these particles seem to be small, relatively unaltered pieces of skeletal structure (Fraundorf *et al.* 1982). Thus, over half the particles are fluffy aggregates of exceedingly small grains held together in a porous and very fragile black matrix whose cumulative composition is opaque and similar to primitive CI/CM meteorites. The remainder in the same mass range seem to be larger, non-porous examples of some of the sulphur-bearing and non-sulphur-bearing grains that make up the common aggregates. Some of the very smallest grains are found to be unmetamorphosed enstatite whiskers and platelets indicative of direct gas-to-solid condensation in a highly reducing environment. But a variety of oxidation states evidently existed during the formation process and the presence of amorphous crystals is suggestive of processing at lower temperatures as well. Indeed, the presence of lower melting point volatiles in the pores would require that there were several temperature régimes during formation and it may be that the presence of amorphous crystals accounts for the intrinsically weak structures (Smoluchowski 1980). Either a gathering of particles from a wide range of initial environments is indicated therefore, or condensation takes place in a medium whose average physical and chemical state undergoes significant evolution during the formation process. Thus, the connected skeletal structure may be due to separate interstellar grains, with volatile mantles, that merged during cold accretion or it may have been built up from the separate refractory cores that developed in a dense cooling medium. The choice between such alternatives is not yet settled but there seems to be little doubt now that the stratospheric particles studied in the laboratory do indeed enter the atmosphere from the Zodiacal Cloud and that they typify the material of which meteors and fireballs are largely composed.

High concentrations of implanted helium, neon and argon are commonly detected in stratospheric particles consistent with exposure to the solar wind for up to 50 years (Fraundorf *et al.* 1982), though a primordial bombardment of individual particles before their possible accretion cannot also be excluded. On either of the above modes of formation however, it is clear that the lifetimes of typical dust particles in the interplanetary medium are considerably shorter than the collision times associated with ordinary basaltic material. Searches have also been conducted for nuclear tracks in interplanetary dust particles due to solar flares but with varying success (Fraundorf *et al.* 1982). Thus, for most of the porous aggregates of chondritic particles examined, where something like 30 tracks μm^{-2} would be expected for a residence time of 10 ka, none have been identified. Nevertheless, in two cases, *ca.* 10% of those examined, high track densities have been found, indicating exposure ages of *ca.* 1–10 ka (Bradley *et al.* 1984). The absence of identifiable tracks in the other examined bodies could be due to track annealing on atmospheric entry but this is considered to be unlikely given the generally rather low level of physical alteration observed; alternatively the average space exposure of these particles at 1 AU is orders of magnitude less than 10^4 ka, as might be expected for bodies with

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their demonstrably fragile structure. These investigations are of course still very much in their infancy but the evidence from laboratory examinations does not apparently exclude a mixed interplanetary dust complex comprising a longer lived meteoritic component together with a rapidly evolving meteoroidal component.

4. Replenishing the dust complex

According to the recent calculations by Grun *et al.* (1986), there is an unreplenished loss of *ca.* 10^9 t a^{-1} from particles in the interplanetary dust complex with $10^{-5} \leqslant m \leqslant 10^2$ g, assuming $\alpha \geqslant 2$ (see (1)). Evidently such a loss may be compensated by the occasional erosion of much larger bodies of low compressive strength provided that $1 \leqslant \alpha \leqslant 2$, as observed. Thus, if we consider target bodies of mass of at least m_1 undergoing catastrophic collisions with masses of at least m_2, where

$$m_1 = \Gamma m_2 \tag{2}$$

and we tentatively assume $\Gamma \approx 10^{10}$ for material whose compressive strength is *ca.* 10^{-4} that of basalt (cf. table IV in Grun *et al.* 1986), then the number of masses of at least m_1 involved in destructive collisions per unit time is given approximately by:

$$N(\geqslant m_1) \approx Vn(\geqslant m_1)\, n(\geqslant m_2)\, r_{12}^2 u_{12}, \tag{3}$$

where $n(\geqslant m_i)$ is the space density of bodies of mass of at least m_i and radius of at least r_i, V is the volume of the Zodiacal Cloud and u_{12} is an appropriate encounter velocity. Normalizing to the space density of objects of 10^4 g striking the Moon during the period 1970–6 (Dorman *et al.* 1978),

$$n(\geqslant 10^4\,g) \approx 10^{-29}\ \mathrm{cm}^{-3} \tag{4}$$

and assuming a material density of *ca.* 0.1–1 g cm^{-3}, $V \approx 10^{41}\ \mathrm{cm}^3$ and $u_{12} \approx 20$ km s^{-1}, we find that $N(\geqslant 10^{13}$ g) and $N(\geqslant 10^{17}$ g) are of the order of one per year for values of α equal to 1.75 and 1.5 respectively. These values bracket the observed mass distribution index of fireballs and indicate that if we make due allowance for the radial dependence of $n(\geqslant m_i)$ in the Zodiacal Cloud, we might expect masses of at least 10^{16} g, which are destroyed at the rate of approximately one per year, would be more than adequate to sustain the current loss from the existing interplanetary dust complex.

For unrestrained dispersal, however, the collision energy has to be distributed more or less uniformly throughout the disrupted body *and* exceed the gravitational binding energy. Masses of *ca.* 10^{16} g are in fact close to the upper limit of $m_1 \approx r_1^2 u_{12} \Gamma^{-1} G^{-1}$ capable of total disruption, the velocity of dispersal being at least 10^{-4} km s^{-1}. It follows that bodies of at least 10^{17} g undergoing erosive collisions somewhat less frequently than one per year and dispersing material at at least 10^{-3} km s^{-1} are the most probable source replenishing the Zodiacal Cloud at *ca.* 10^{15} g a^{-1}. It is not to be expected of course that the collision energy will be uniformly distributed among the eroded fragments and escape velocities considerably greater than 10^{-3} km s^{-1} may be anticipated, even as large as 1 km s^{-1}. Such velocities result in the dispersal of material into a broad tube around a typical short-period orbit within the course of only a very few circuits giving a typical cross-section radius at the Earth of at least 0.5 AU (see, for example, table I of Plavec 1954). The question naturally arises therefore whether there is any evidence for these postulated events, involving the production and rapid dispersal of *ca.* 10^{15} g meteoroid swarms every few years.

Comet Biela, first detected in 1772, was observed disrupting violently in 1845 and since the has never been seen (see, for example, Lovell 1954). However, in 1872 and 1885, when th Earth crossed the orbit of the vanished comet, there were tremendous displays of meteor: apparently comparable to the famous Leonid showers in 1799 and 1833. The disappearanc of Comet Biela, together with its strange disruption, gives the Andromedid (i.e. Bielid) showe a unique position in meteor astronomy and is widely regarded as evidence of an event tha involved the more or less total break-up of a body whose mass would have been, if it were a average short-period comet, *ca.* 10^{16} g. On the face of it, therefore, the demise of Comet Biel could have been a particularly conspicuous example of the proposed replenishment events. T set this example in perspective, however, we also list all the passages of the Earth through dens meteor swarms since 1800 and the current passages through major tube-shaped meteor swarms see table 2, adapted from Kresak (1980). The quantities D and E refer respectively to the widt of the tube and the maximum relative enhancement above the sporadic background. Some c the streams are so narrow and the measurements so uncertain that the values of E must b regarded as indicative rather than true; nevertheless, even here, the Biela shower is clearly notable event.

At the same time though, it is also apparent that if the Taurid stream were confined to

TABLE 2. DENSEST METEOR SWARMS SINCE 1800 AND MAJOR ANNUAL METEOR STREAMS†

swarm/stream		parent comet	P/years	q/AU	D/AU‡	E§
Andromedids	1885	Biela	6.6	0.87	0.0070	230
Draconids	1933	Giaccobini–Zinner	6.6	1.00	0.0025	180
Andromedids	1872	Biela	6.7	0.87	0.0070	120
Draconids	1946	Giacobini–Zinner	6.6	1.00	0.0015	60
Leonids	1966	Tempel–Tuttle	32.9	0.98	0.0008	40
Leonids	1833	Tempel–Tuttle	33.1	0.98	0.0010	14
Andromedids	1892	Biela	6.6	0.86	0.0010	6
τ Herculids	1930	Schwassman–W.3	5.4	1.01	0.0015	2.3
Andromedids	1847	Biela	6.6	0.86	0.0007	2.3
Bootids	1916	Pons–Winnecke	5.9	0.97	0.0003	2.1
Draconids	1952	Giacobini–Zinner	6.4	0.99	0.0002	1.8
Andromedids	1838	Biela	6.6	0.88	0.0004	1.6
Andromedids	1899	Biela	6.7	0.86	0.0004	1.6
Lyrids	1803	Thatcher	415.5	0.92	0.0005	1.4
Leonids	1867	Tempel–Tuttle	33.5	0.98	0.0002	1.4
Leonids	1965	Tempel–Tuttle	32.9	0.98	0.0030	1.4
Geminids		?	1.6	0.13	0.14	0.19
Quadrantids		?	5.4	0.98	0.03	0.17
ξ Perseids		?	2.0	0.34	0.12	0.11
β Taurids		Encke	3.3	0.34	0.20	0.07
Arietids		?	2.0	0.09	0.18	0.06
Taurids		?	3.3	0.34	0.85	0.05
δ Aquarids		?	4.6	0.08	0.30	0.05
Perseids		Swift-Tuttle	120.0	0.96	0.30	0.035
Ursids		Tuttle	13.8	1.02	0.12	0.023
Lyrids		Thatcher	415.5	0.92	0.04	0.014
μ Aquarids		Halley	76.1	0.59	0.20	0.010
Orionids		Halley	76.1	0.59	0.25	0.007
Leonids		Tempel–Tuttle	32.9	0.98	0.02	0.003

† Based on Kresak (1980).
‡ Typical half-width of stream.
§ Relative enhancement above sporadic background.

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volume similar to that of the Andromedids, its *annual* relative enhancement would be the equal of the Andromedids in 1885. Thus, to the extent that visible phenomena associated with typical disruption events may survive for a decade or so (cf. Comet Biela), it is evidently possible that the Taurid stream is sustained by lesser events of the same kind which happen at average intervals of a few years. There is of course no question of *comet* disruption in the case of the Taurid stream since such bodies are not observed (except Comet Encke), but that does not exclude the possibility that unsighted dead comets with freshly black surfaces may be involved. If this is indeed the case, such events would correspond to those predicted above and would lead one to concur with Kresak's comment (Kresak 1980) that the Taurid stream, by reason of its width, is quite abnormal and potentially a uniquely rich source for the interplanetary meteoroidal complex. More recently, Stohl (1983) has shown that a substantial portion of the sporadic meteor flux, commonly associated with the Zodiacal Cloud, may be concentrated in an extremely broad ecliptical stream of meteoroids centred on the Taurids. In fact, he demonstrates that the broad stream is double, so it may have arisen from the asteroid belt fragmentation experienced five thousand years ago by the progenitor of Comet Encke (Whipple & Hamid 1952), already believed by several authors to have been a very large body (Whipple 1967; Delsemme 1976; Kresak 1980; Clube & Napier 1984; Olsson-Steele 1986). There seems to be little doubt that the evidence favours strongly the Taurid stream as the likely principal source of the postulated events. But such data do not prove that the postulated events actually take place.

Recently, however, there appear to have been at least three well-documented observations of conspicuous short-lived meteoroid swarms within the broad ecliptical stream; see table 3. In each case, the observational technique employed has been listed together with estimates of

TABLE 3. ENCOUNTERS WITH SHORT-LIVED METEOROIDAL SWARMS

date	detection technique	$\frac{\sigma}{\text{cm}^{-3}}$	$\frac{m}{\text{g}}$	$\frac{V_s}{\text{cm}^3}$	$\frac{M_s}{\text{g}}$	Taurids ?
April 1964	meteor radar[1,2]	10^{-23}	10^{-6}	10^{41}	$10^{15.5}$	no
November 1974	explorer 46[3] (impact detector)	10^{-13}	10^{-15}	10^{37}	$10^{15.5}$	yes
June 1975	lunar seismic detector[4]	10^{-29}	10^4-10^6	10^{37}	10^{16}	yes

References: 1. Ellyett & Keay 1964; 2. McIntosh & Millman 1964; 3. Singer & Stanley 1980; 4. Dorman *et al.* 1978.

the space density of particles observed (σ), their mass (m) and the size of the swarm (V_s). In those instances where $m \leqslant 10^2$ g, the equivalent space density of 10^2 g objects has been deduced taking the relative particle fluxes from table 4 as standard. If these inferred objects or observed 'particles' with $m \geqslant 10^2$ g represent the low mass end of a meteoroid distribution ($\alpha = 1.67$) dominated by a single large body, the cumulative mass M_s of the swarm may be also readily deduced. In each independent case, it may be noted that the mass of the swarm M_s is comparable with that predicted for a typical erosion event every few years. In practice, of course, it seems very likely that the second and third events in table 3 may not be physically independent, though this fact has not previously been remarked upon, and that the differing values of M_s give some indication of the likely precision of the present calculations, which can

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TABLE 4. RELATIVE PARTICLE FLUX†

m/g	$n(m)$/cm^{-3}	α
10^{-17}	10^{-11}	
		1.5
10^{-9}	10^{-15}	
		2.2
10^{2}	10^{-28}	
		1.67

† Based on Dohnanyi (1978).

indeed be no more than suggestive given the approximations in the modelling. Nevertheless, on the basis of quite simple assumptions, consistent with what is known about interplanetary dust, these unexpectedly observed swarms during the most recent decades, seem to be impressively like the ones anticipated from general arguments regarding the origin of the Zodiacal Cloud. The speculation that the interplanetary dust complex in the Solar System is maintained by the regular fragmentation of substantial meteoroids in the Taurid stream seems to be not unjustified.

5. PAST AND FUTURE IMPLICATIONS

Arguments based on (i) the exposure ages of interplanetary dust particles collected from the stratosphere, (ii) the compressive strength of the commonest fireballs, (iii) the existence of a broad ecliptic stream centred on the Taurids and (iv) the observation of substantial short-lived meteoroid swarms therein, have led to the suggestion in this paper that the Zodiacal Cloud is a predominantly meteoroidal complex and not a meteoritic complex as commonly supposed. A replenishment model based on this assumption has thus been constructed which is consistent with (i) *in situ* measurements of the interplanetary dust, (ii) Zodiacal Cloud brightness, (iii) lunar microcratering, (iv) siderophile deposits in deep-sea sediments, and (v) current physical and dynamical relations between comet, asteroid and fireball populations. It is a feature of the model that the Taurid meteor stream is a prominent source of large eroding meteoroids and that fireballs associated with the core of the stream are likely to be weaker on average than those that have survived collisionally induced dispersal into the broad ecliptic stream. This is, in fact, an observed property of the Taurid fireball distribution (Wetherill & ReVelle 1982; section III; cf. Hindley, 1972) though their strength in general somewhat exceeds that of random fireballs on account of their possibly greater carbonaceous content.

If, in accord with the strength of these fireballs, we assume that a typical swarm decays exponentially on a characteristic timescale of *ca.* 10 years (cf. the collisional timescale of *ca.* 100 ka derived by Grun *et al.* (1986), assuming material like basalt), it is readily shown that enhancements of the Taurid fireball flux by factors of a few over periods of 10^2–10^3 years would arise at corresponding average intervals of 1–10 ka following the disruption of individual meteoroid masses of *ca.* 10^3–10^4 times that of the commonly observed swarms that occur at *ca.* 10 year intervals and are responsible for maintaining the background stream. A conspicuous centuries-long enhancement of the Taurid fireball flux, typical of such a disruption within the last 1–2 millennia, has been recorded in the eleventh century A.D. (Astapovic & Terenteva 1968), implying the existence over an indeterminate period at this time of a particularly dense meteoroid swarm. This finding clearly places in a new light possible coincidences with the daytime Taurids around this epoch, particularly a terrestrial encounter in A.D. 793 when it was noted by a chronicler that '...excessive whirlwinds, lightning storms and fiery dragons were seen flying in the sky' (see, for example, Brondsted 1965) and a lunar encounter in 1178 when a significant crater-forming event may have been observed (see, for example, Brecher 1984; Clube & Napier 1984, note added in revision). It also raises questions concerning the attention given to fireball activity during much the same period (*ca.* 600–1000) by Chinese astronomers (Schafer 1977; cf. Biot 1848). In addition, it is significant that the late classical period is known to have coincided with a similar period of considerable meteoric activity (Cornford 1952), following an earlier time when the Zodiacal Cloud was probably enhanced. Thus, the discussion by Aristotle concerning the properties of the 'Milky Way' up to 400 B.C. is clearly anomalous (Jaki 1973) and if its proposed replenishment by comets and location in the apparent path of the Sun are taken *inter alia* at face value, there is good evidence that an earlier, conspicuous zodiacal cloud was being described (Bailey *et al.* 1986; Clube & Napier 1984). Despite the unavoidably circumstantial nature of much of this evidence, the three most recent millennia are not inconsistent with a model in which the interplanetary dust complex is replenished by a stochastic time-sequence of disintegrating meteoroid swarms in the Taurid stream.

If the Moon encounters *ca.* 40 meteoroids of mass at least 10^5 g (Dorman *et al.* 1978) during the passage of a disintegrating swarm and *ca.* 10 swarms of this or greater magnitude are produced during the course of a century, the total number of such bodies produced during the course of a century, the total number of such bodies encountered by the Earth is approximately 20000 $(100\ \mathrm{a})^{-1}$. Extrapolating the observed mass distribution of fireballs, this corresponds to one or two bodies of mass at least 10^{11} g striking the Earth per 100 years, in satisfactory accord with the single landfall at Tunguska during the twentieth century (Krinov 1966). The lunar surface on which craters are counted is at least 4 Ga old and the inferred flux of meteoroids of at least 10^{11} g is usually time averaged over this period. But if the episodic theory referred to previously (Clube & Napier 1986*a*) is correct, most of this cratering will be bunched in impact episodes during which the average flux will be at least an order of magnitude higher. Because the overall 'Tunguska' flux is approximately 1 per 500 years (Shoemaker 1983), the implied current rate is again 1–2 per century and in good agreement with the land fall this century. Thus, both the 'recent' historical past and the long-term terrestrial–lunar record are compatible with regularly disintegrating meteroid swarms sustained by an eposidic sequence of giant comets.

It needs to be emphasized, however, that although the model arrived at here is constrained by available observational evidence, it is also predicated upon an *assumed* compressive strength for meteoroidal material for which there is no laboratory measurement. Nevertheless, if the theory is accurate at the order-of-magnitude level, there are several significant predictions which, failing these independent measurements, would now serve to test its authenticity:

(1) Relatively high cosmic dust deposition rates at least $10^5\ \mathrm{t\ a^{-1}}$ will have occurred within the most recent ~ 10–100 ka corresponding to the dispersal of the latest giant comet. These may correlate with the most recent ice-age *ca.* 10–20 ka ago (*cf.* La Violette 1983; Clube & Napier 1984; 1986*a*).

(2) At least one multiple Tunguska bombardment of the Earth (by 10^2–10^3 meteoroids of at least 10^{11} g) will have occurred during the last 5 ka, giving rise to widespread incineration and a probable climatic recession (Clube & Napier 1986*b*). Such a process bears comparison with a similar event at the Cretaceous–Tertiary boundary (Wolbach *et al.* 1985) and indicates that

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rare swarm encounters are probably typical low-level extinction events. Although the involvement of a *ca.* 10 km missile with the K–T boundary (see, for example, Alvarez *et al.* 1980) is not excluded by this hypothesis, the failure so far to discover any large crater corresponding to this epoch may not be surprising.

(3) *Future* multiple Tunguska bombardments are still possible on the present model. Their prediction would be facilitated by a search for the meteoroidal remains of the latest giant comet. These may include a large carbonaceous asteroid ($R \lesssim 100$ km, albedo *ca.* 0.02) in the Taurid meteor stream, which could be reactivated as a weak comet from time to time by particularly violent impacts. It is not known now whether any reactivations have been observed during the last few thousand years but a search in the Taurid stream for the putative minor planet (for which the name Chronos is proposed since its regular motion will have been observed in the past) could bring a return on the investment of telescope time.

(4) If the stochastic erosion model for the most recent giant comet, otherwise proto-Encke, is correct, Comet Encke may itself be an asteroid that was reactivated two centuries ago. Also, because a node of the latter's orbit passed through the Earth's orbit at the time of Christ (cf. Whipple & Hamid 1952), this body may have been unexpectedly visible at this time.

6. Conclusion

A wide range of evidence now indicates that a large cometary or D-class asteroid in the Taurid meteor stream may be the primary source of the interplanetary meteoroidal dust complex. It is recommended that a search be conducted for this particular minor planet to place models of the dust in the immediate solar environment on a secure quantitative basis. If Chronos is found, the probably dominant role of large differentiated comets in Earth history would be reinforced and the question of the origin of such bodies, in which most of the cometary mass resides, would overtake that of their more common but less significant counterparts, ordinary comets. Thus, it has been suggested in this paper that the fragile, skeletal structure associated with the stratospheric particles from the Zodiacal Cloud may be understood in terms of condensation as much as accretion. It follows that the search would not only be of interest for its own sake but for its potential contribution to the understanding of a fundamental astrophysical process.

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Discussion

M. A. Saunders. In the April 1986 issue of *Geophys. Res. Lett.*, L. A. Frank and co-workers at Iowa suggest that small cometesimals of mass *ca.* 100 t are impacting the Earth's upper atmosphere at a global rate of *ca.* 20 min^{-1}. Is such a global mass accretion rate of *ca.* 10^{12} kg a^{-1} feasible in view of our current knowledge of matter distribution in space?

S. V. M. Clube. An accretion rate of *ca.* 10^{12} kg a^{-1} seems now to be irreconcilable with either the observed chondritic deposition rate or the exospheric diffusion rate of hydrogen. The cometesimal masses may therefore have been overestimated by a factor of *ca.* 10^6. The actual observations are of large decreases in atmospheric UV dayglow due to the transient appearance of *ca.* 50 km absorbing molecular clouds at *ca.* 300 km altitude. It may be noted that the discoverers have not excluded the possibility that substantially smaller masses of incoming material may be involved, needing only to catalyse recombination of the dominant O I species in the atmosphere. However, no reasonable catalyst has yet been identified.

J. Darius (*Science Museum, London, U.K.*). Surely Dr Clube's interpretation of the aristotelian Milky Way, for which he would have us read Zodiacal Cloud, is inconsistent with injection of large comets on a timescale of *ca.* 100 ka, which he considers to be linked to the lifetime of the Zodiacal Cloud.

S. V. M. Clube. The phenomena referred to by Aristotle in his *Meteorologica* and apparently by previous natural philosophers as well (see Bailey *et al.* 1986) are thought to be due to a temporary enhancement of the Zodiacal Cloud during the preceding millennium. If so, it may be understood in terms of the *continuing* fragmentation of the most recent giant comet, whose remnant is now believed to be still circulating in the Taurid stream.

J. Darius. I was mildly perturbed at the prospect that a large comet should have been coincidentally deposited in the 4th century B.C. just in time for Aristotle to compose his *Meteorologica*!

Sir Bernard Lovell, F.R.S. (*Jodrell Bank, Macclesfield, Cheshire, U.K.*). The daytime meteor stream of the β-Taurids of late June and the autumn meteor stream of the Taurids have orbits similar to that of Encke's Comet. Thus any of the special phenomena mentioned by Dr Clube, which he suggests are related to the comet, should be identifiable both in June and October.

S. V. M. Clube. Weakly bound material emanating from the progenitor of Comet Encke into the broad tube surrounding the Taurid stream may well be observed at both intersections with the Earth's orbit.

F. L. Whipple (*Smithsonian Institution, Washington, D.C., U.S.A.*). Encke's Comet still seems to be important to the Zodiacal Cloud. A more direct measure might be the discovery in the historical records of intense meteor streams when the Earth crossed the comet's orbit within about 200 years of the birth of Christ. These magnificent showers should have been separated 10 years for a few repetitions.

E. Anders (*Enrico Fermi Institute, University of Chicago, U.S.A.*). There exist some recent data bearing on the contribution of large bodies to the total meteoritic influx. Kyte & Wasson (1986) have measured iridium in a deep-sea core covering the period 33–67 Ma ago, and found only a single peak, at 65 Ma, representing the terminal Cretaceous (K–T) impact. Everywhere else the influx rate of extraterrestrial Ir remained essentially constant, corresponding to a global influx of $(7.7 \pm 2.5) \times 10^{10}$ g a^{-1} of chondritic matter. This agrees closely with an earlier value of $(9.6 \pm 4.8) \times 10^{10}$ g a^{-1} (Barker & Anders 1968), based on five cores representing the past 1–2 Ma, which has been recalculated for revised sedimentation rates (Ku *et al.* 1968). Apparently there has been no secular change in the influx rate.

It is curious that no other peaks show up in the record. The K–T body, of mass 1×10^{18} g (Alvarez *et al.* 1980) gave an Ir peak 30 times above background. A body of one tenth this mass would have given a peak 3 times above background, which would be readily detectable. From the relation of Wetherill & Shoemaker (1982), four bodies of at least 10^{17} g should have fallen during the 34 Ma interval represented by this core, yet only one (the K–T body) shows up in the data. Perhaps this is merely a statistical fluke; on the other hand, it is conceivable that bodies smaller than 10 km do not distribute their debris globally, but leave much of it near the impact site. This seems to be true of a 0.1–0.5 km body that fell 2.3 Ma ago (Kyte & Brownlee 1985), but without further data, one cannot tell at which size global distribution of ejecta commences.

These data also speak against the hypothesis that a shower of comets was responsible for the K–T 'event'. Davies *et al.* (1964) estimate a cloud of some 2×10^9 comets, yielding some 25 Earth impacts in 1–3 Ma. However, such widely spaced impacts – or even the dust from the remaining comets – would give a broad peak rather than the sharp spike observed.

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S. V. M. Clube. The standard deviation of the global influx is apparently not instrumental in origin (Barker & Anders 1968), thus the available observations are consistent with a stochastic time sequence of at least 10^{16} g global inputs of chondritic material over periods of *ca.* 100 ka upon a background level up to 10^{10} g a^{-1}, each input being due to the degradation of a separate large meteoroid of at least 10^{21} g. On this hypothesis, the K–T event may be due to a particularly destructive fragmentation producing an exceptionally dense meteor stream and thus only coincidentally correlated with a large crater-producing impactor, if at all. More importantly, dense atmospheric veils of global extent are, on the present theory, comparatively frequent (*ca.* 10 per large meteoroid), the effects probably saturating at inputs of at least 10^{16} g.

Even on the present theory therefore the terminal Cretaceous Ir has to be attributed to a singular event but it is possible that the specially drastic effects associated with the K–T event are not specifically due to an atmospheric veil, as suggested by Alvarez *et al.*

Whether or not the data speak against 'comet showers' depends on whether long-term galactic modulations (e.g. 30, 250 Ma) are detectable in the otherwise stochastic time sequence degraded by bioturbation. Any such finding would not conflict with the 'narrowness' of the K–T event since the latter may take place within a concentration of lower Ir peaks extended over several million years, consistent with an evolutionary decline before the event itself. Although the relation between such predictions and the Ir cores is unavoidably speculative at this time, 'comet showers' of the kind proposed by Davis *et al.* can almost certainly be ruled out because they involve hypotheses superfluous to the astronomical requirements, namely a companion star and an 'inner cloud' of comets, while also overlooking the dominant role played by asteroids in the cratering record (cf. Clube & Napier 1984).

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Note added in proof (*June* 1987). Since this paper was completed, comet 'trails', as distinct from meteor streams, have been detected with IRAS (Sykes *et al.* 1986). It has been suggested that these trails may be sustained by material released during perihelion passages, as for meteor streams, though it is possible that they are more closely associated with swarm production of the kind envisaged in this paper.

Additional reference

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