Inferring Sources in the Interplanetary Dust Cloud, from Observations and Simulations of Zodiacal Light and Thermal Emission

A.C. Levasseur-Regourd • J. Lasue

Abstract Interplanetary dust particles physical properties may be approached through observations of the solar light they scatter, specially its polarization, and of their thermal emission. Results, at least near the ecliptic plane, on polarization phase curves and on the heliocentric dependence of the local spatial density, albedo, polarization and temperature are summarized. As far as interpretations through simulations are concerned, a very good fit of the polarization phase curve near 1.5 AU is obtained for a mixture of silicates and more absorbing organics material, with a significant amount of fluffy aggregates. In the 1.5-0.5 AU solar distance range, the temperature variation suggests the presence of a large amount of absorbing organic compounds, while the decrease of the polarization with decreasing solar distance is indeed compatible with a decrease of the organics towards the Sun. Such results are in favor of the predominance of dust of cometary origin in the interplanetary dust cloud, at least below 1.5 AU. The implication of these results on the delivery of complex organic molecules on Earth during the LHB epoch, when the spatial density of the interplanetary dust cloud was orders of magnitude greater than today, is discussed.

Keywords interplanetary dust · light scattering properties · thermal properties · atmospheric entry · comets · asteroids · meteoroids

1 Introduction

The question of the origin of the dust particles that are permanently replenishing the interplanetary dust cloud, thus allowing the appearance of the zodiacal light, has been extensively discussed all over the past years. Before the 1980s, the main source was assumed to be the dust released by active cometary nuclei in the interplanetary dust cloud (Whipple, 1955). In 1983, the detection of asteroidal bands and cometary trails by the Infrared Astronomical Satellite (IRAS) has allowed some authors to estimate that the main source was dust released by asteroidal collisions or disruptions (see e.g. Sykes and Greenberg, 1986). While minor sources of dust, such as dust from Jupiter and Saturn systems and dust of interstellar origin, have also been detected by Ulysses, Galileo and Cassini spacecraft (see e.g. Grün et al., 2001 and references therein; Taylor et al., 1996), the main source of interplanetary dust in the Earth environment has remained an open question.

It is most likely that the sources of most meteor streams are comet nuclei and that those of most meteorites are asteroidal fragments. Nevertheless, it is difficult to estimate whether comets or asteroids predominantly contribute to the zodiacal cloud, even in the vicinity of the Earth, and finally to know

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what are the sources of sporadic meteors and of micrometeorites. These questions are all the more important that the interplanetary dust cloud, even if assumed to be stationary, is likely to undergo numerous evolution processes, e.g. with fragmentation, weathering and partial sublimation of its dust particles. We will propose some answers through an approach that relies upon inversion of observations of the near-Earth zodiacal light and zodiacal thermal emission, and upon interpretations through numerical simulations. Finally, we will compare our results with those obtained for cometary dust and for the interplanetary dust through other approaches, and assess their implication for the delivery of carbonaceous compounds to the early Earth.

2 Results Derived From Observations

Observations from Earth's orbit in the visual and near infrared domains allow for the detection of the so-called zodiacal light and zodiacal thermal emission (see e.g. Levasseur-Regourd et al., 2001 and references therein). The zodiacal light is a faint veil of solar light, brighter towards the Sun and the near-ecliptic invariant plane of the solar system. The zodiacal thermal emission is the most prominent component of the light of the night sky in the 5 to 100 μm region, at least away from the galactic plane.

2.1. Near-Earth Zodiacal Light and Zodiacal Thermal Emission

The zodiacal light actually originates in the scattering of solar light by dust particles. The sharp increase of its brightness *Z*, towards the Sun and the invariant plane, indicates an increase in the space density of the interplanetary dust cloud, which forms a thick disk around the Sun. A slight enhancement in brightness, the gegenschein, also takes place in the anti-solar region; it corresponds to a backscattering effect. As expected from the scattering of randomly polarized solar light in an optically thin medium, the zodiacal light is partially linearly polarized. The polarization *P* is defined as the ratio of the difference to the sum of the brightness components respectively perpendicular and parallel to the scattering plane; it is slightly negative in the gegenschein region.

The brightness *Z* (in W m^{-2} sr^{-1} μm^{-1}) and the polarization *P* (in percent), as determined as functions of the helio-ecliptic latitude and ecliptic longitude, after correction for the invariant plane inclination (e.g. Leinert et al., 1998; Levasseur-Regourd et al., 2001), provide an estimation of the foreground noise induced by the zodiacal light, together with an optimization of the epochs of observations of faint extended astronomical objects. The zodiacal thermal emission, whose maximum is slightly above 10 μm, as observed from the Earth environment, corresponds to a temperature of about 250 K along the line-of-of sight. In the very near infrared domain, by 0.8 to 1.2 μm, the thermal emission is still negligible and the scattered light prevails. For larger wavelengths, observation of the thermal emission (which is isotropic) provides an easier detection of local heterogeneities than brightness emission, as recently illustrated by the detection from Spitzer spacecraft of the dust trail of comet 67P/Churyumov-Gerasimenko, the target of the Rosetta mission (Kelley et al., 2008).

2.2. Data Inversion and Local Results

Since the concentration and the temperature of the dust are changing significantly with the solar distance R, the local brightness and thermal emission are expected to vary along the line-of-sight for Earth or near-Earth based observations. Besides, it cannot be assumed that the interplanetary dust cloud is homogeneous and that the properties of the dust (e.g. albedo, size distribution) are the same everywhere in the cloud. The brightness, as well as its perpendicular and parallel components, and the thermal emission are thus integrals that need to be, at least partially, inverted. A rigorous inversion is feasible, for a line-of-sight tangent to the direction of motion of the observer and for the section of the line-of-sight where the observer is located. This approach has, up to now, provided bulk values of some local properties in the vicinity of the Earth (Table 1). To retrieve local information in regions that are not located on the orbit of the Earth, inversion mathematical methods, leading to comparable results, have been independently initiated by Dumont and Levasseur-Regourd (1988) and by Lumme (2000).

Table 1. Parameters relevant to the local properties of the interplanetary dust particles and their dependence with distance to the Sun *R* (0.3 to 1.5 AU range) in the near-ecliptic invariant plane (adapted from Levasseur-Regourd et al., 2001): Linear polarization *P* at 90° phase angle, temperature *T*, geometric albedo *A* and space density.

Parameter	Heliocentic gradient	Comment
$P_{90°}(R)$	$30\ R^{+0.5 \pm 0.1}$ (%)	Evolution of local polarization
$T(R)$	$250\ R^{-0.36 \pm 0.03}$ (K)	Not a perfect black-body
$A(R)$	$A_0\ R^{-0.34 \pm 0.05}$	Evolution of geometric albedo
Space density(R)	$10^{-17} R^{-0.93 \pm 0.07}$ (kg m^{-3})	Most likely 1/*R*

One result is related to the shape of the local polarimetric phase curve (see Fig. 11 in Levasseur-Regourd et al., 2001). At 1.5 AU from the Sun in the invariant plane, it is smooth, with a slight negative branch, an inversion angle in the 15° to 20° range and a positive branch with a maximum of about 30 percent. This trend indicates that the scattering particles are irregular with a size greater than the wavelength of the observations, i.e. about 1 µm; it also suggests, assuming that the Umov empirical law is valid, that the particles have quite low an albedo. Another key result is related to the variations with the solar distance R (between 0.3 and 1.5 AU) of some local properties, which approximately follow power laws. The trend obtained for the local polarization at 90° phase angle, a ratio independent upon the concentration (see Fig. 5 in Levasseur-Regourd et al., 1991), establishes that the interplanetary dust cloud is heterogeneous, i.e. that the intrinsic properties of the dust vary with R. Since the dust particles spiral towards the Sun under Poynting-Robertson drag (or are blown away by solar radiation pressure), it can be assumed that the intrinsic properties vary with time and that the dust particles suffer a significant temporal evolution.

3 Interpretation Through Numerical Simulations

3.1 Zodiacal Light Results

Results need to be interpreted through appropriate simulations, with tentatively realistic assumptions about the size distribution, the composition and the structure of the particles (Levasseur-Regourd et al., 2007; Lasue et al., 2007). The size distribution may be assumed to be similar to that derived from in-situ measurements by Grün et al. (2001), showing a size distribution with a few branches following power-laws. We have approximated this size distribution with power-laws of index about -3 for sizes below 20 µm and about -4.4 for larger sizes. A predominance of silicates, with an average complex refractive index of about (1.62 + 0.03i) at 550 nm, and absorbing organic molecules or carbon, with an average complex refractive index of about (1.88 + 0.1i) at 550 nm, has been suggested from an analysis of previous studies of IDPs and micrometeorites by Lasue et al. (2007). The particles may either be compact, as expected for fragments resulting from asteroidal collisions and for some cometary dust, or constituted of aggregates, as expected for other cometary dust particles (as confirmed by Stardust mission, see also paragraph 4.1).

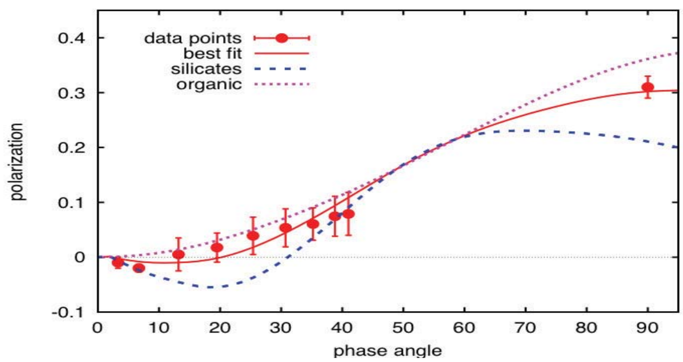

Figure 1. Best fit for the local polarimetric observations at 1.5 AU near the ecliptic. The dashed curve corresponds to non-absorbing silicates, the dotted curve to absorbing organic material. The solid curve is the best fit obtained by mixing 40% of organics and 60% of silicates in mass. (adapted from Lasue et al. 2007)

A combination of T-matrix calculations for small particles and ray-tracing simulations for larger particles is used to compute the light scattering from a cloud of dust particles built up of prolate spheroids and fractal aggregates of them. The best fit to the observational results constraints, at 1 AU in the invariant plane, the particles composition to 25-50% of organics in mass, and conversely to 75-50% of silicates in mass. The best estimate of the contribution of aggregated dust particles, simulated by irregular aggregates of spheroids randomly oriented, correspond to -at least- 20% of aggregates in mass (Lasue et al., 2007). This in turn, as extrapolated from the bulbous to single track ratio from the Stardust aerogel analyses (35% of bulbous tracks; Hörz et al., 2006; Burchell et al., 2008), would correspond to at least 50% in mass for the contribution of dust particles from comets.

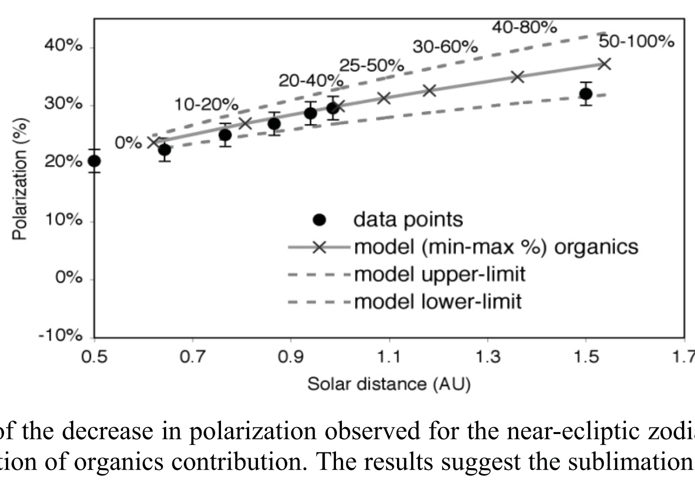

Figure 2. Interpretation of the decrease in polarization observed for the near-ecliptic zodiacal dust between 1.5 and 0.5 AU through an evolution of organics contribution. The results suggest the sublimation of the organics present in the particles.

3.2 Thermal Emission Results

The temperature variations with R, as deduced from the observations, do not follow a black-body relationship. This certainly indicates particular properties of the zodiacal dust cloud. The thermal equilibrium temperature of dust particles can be computed by equating the incident and emitted light integrated over a large range of wavelengths, λ, (typically from 0.1 to 1000 µm). At a distance R (in AU) from the Sun, this is obtained by solving the expression:

$$\left(\frac{r}{R}\right)^2 \int_0^\infty B(\lambda,T_S)Q_{abs}(a,\lambda)d\lambda = \varsigma \int_0^\infty B(\lambda,T)Q_{abs}(a,\lambda)d\lambda \qquad (1)$$

where r is the radius of the Sun, $B(\lambda,T)$ the Planck function, T_S the solar surface temperature, ζ, the ratio of the emitting surface over $\pi a^2/4$, with a the diameter of the emitting particle and $Q_{abs}(a, \lambda)$ the absorption efficiency of a particle with a given optical index (see, e.g. Kolokolova et al., 2004).

The temperature variation with R (for R varying between 0.5 AU and 1.5 AU) of the dust particles is calculated by taking the absorption and emission properties of compact (spheroids) and irregular aggregates (aggregates of spheroids) dust particles with optical indices ranging from low absorbing silicates to highly absorbing carbonaceous compounds. The optical indices are taken to be those of astronomical silicates (Draine & Lee 1984) and refractive organic material (Li & Greenberg 1997). The behavior of the temperature for large particles (size > 100 µm) is always close to the black-body approximation. Only highly absorbing and small particles show a significantly different behavior. The variation with the solar distance is very dependent on the optical properties and size of the particles and less on the actual shape of the particles. The best estimate for the observed variation of temperature (Table 1) corresponds to small particles (effective radius < 2 µm) constituted of highly absorbing carbonaceous compounds such as organics or carbon as shown in Figure 3. Figure 3 also shows the thermal gradient with the solar distance for spheres and spheroids, indicating that the actual shape of the particle does not significantly modify the thermal behavior of the particles between non-absorbing silicates and absorbing organic compounds.

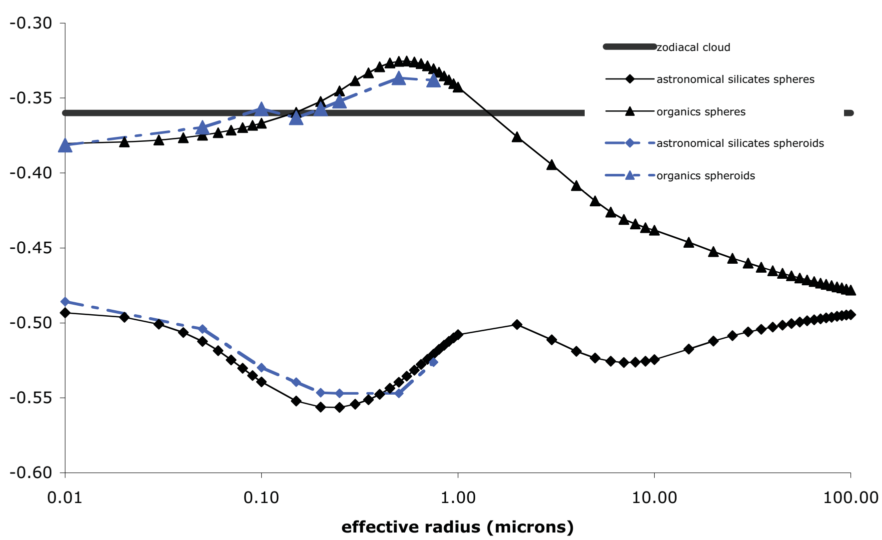

Figure 3. Calculations of the temperature gradient between 0.5 AU and 1.5 AU for two shapes of grains (spheres in black and spheroids in blue) as a function of the equivalent volume size of the grains and for the two different compositions relevant to the interplanetary dust cloud. (adapted from Lasue et al. 2007)

3.3 Significance of the Previous Results

To summarize, the local values derived from observational results, i.e. polarization, geometric albedo, temperature, indicate that, in the near-ecliptic invariant plane and in the 0.5-1.5 AU solar distance range, the dust cloud is heterogeneous and that the dust particles do not behave as black-bodies; they suggest that the dust properties change with time, as most of the particles spiral towards the Sun under Poynting-Robertson drag. Interpretation of the results obtained for the zodiacal light and the zodiacal thermal emission through robust numerical simulations favours the presence of both silicates and organics, with a steady decrease of the organics contribution. While the simulations require a significant amount of aggregates (most likely of cometary origin), it may be added that the *1/R* law derived for the increase of space density with decreasing solar distance is precisely what would be expected for dust particles under Poynting-Robertson drag in their formation region; in the above-mentioned region, significant amounts of cometary dust are actually ejected from active cometary nuclei, while it is unlikely that significant amounts of dust are released by asteroidal collisions.

4 Discussion and Conclusion

4.1 Comparison with Cometary Dust Properties

In-situ Vega and Giotto missions to comet Halley have revealed previously unsuspected properties of the dust ejected by the nucleus of this famous comet. From the dust mass spectrometer on-board Vega, the major constituents have been found to be silicate minerals and organic refractory materials (so-called CHON from their constitutive elements), both in comparable proportions (Kissel et al., 1986). From the optical probe and the dust impact detector on-board Giotto, the dust density has been estimated to be of about 100 kg m^{-3} (Levasseur-Regourd et al., 1999; Fulle et al., 2000). More recently, Stardust mission has provided some ground truth about the structure of the dust collected in comet Wild 2 coma, though the presence of both compact particles and fragile aggregates (Hörz et al., 2006).

As far as remote polarimetric observations are concerned, numerical simulations of the numerous observations of comets Halley and Hale-Bopp, through an approach similar to that described in 3.1, have allowed us to suggest that the dust particles present in the coma of these two comets consist of aggregates and some compact particles, with a percentage in mass of 40-65% of silicates and, conversely, of 60-35% of organics (Lasue et al., 2006; Lasue et al., 2009). In that work, the amount of aggregates present in the comae of comets Hale-Bopp and Halley was estimated to be at least respectively 18% and 10% in mass. We have mentioned in section 2.1 that 35% of the particles collected by Stardust were aggregates. Assuming that aggregate particles originate only from comets, such values would imply that from 50% up to 100% of the particles -both aggregates and compact- present in the zodiacal cloud would be of cometary origin. Experimental simulations have been also attempted to fit the polarimetric observations of comets. They also favour the presence, in addition to some compact silicates, of fluffy aggregates of silicates and carbonaceous compounds (Hadamcik et al., 2007). Finally, the presence of fragile low-density aggregates in the comae of various comets demonstrates that the aggregates noticed in the IDPs collected in the Earth stratosphere are of cometary origin.

4.2 Comparison with Recent Dynamical Studies

Nesvorny et al. (2010) have recently presented a new zodiacal cloud model based on the orbital properties and lifetimes of comets and asteroids, and on the dynamical evolution of dust after ejection, in order of determining the relative contributions of asteroidal and cometary material to the zodiacal cloud. The authors conclude that about 90% of the observed mid-infrared zodiacal thermal emission is produced by particles ejected from Jupiter family comets and that about 10% is produced by Oort cloud comets and/or asteroidal collisions.

While their approach is completely different from ours, and is only constrained by IRAS observations, it is certainly interesting to point out that both approaches establish that particles of asteroidal origin cannot be claimed to be the major source of interplanetary dust. Besides, it may be noticed that the value of about 50% in mass that we obtain for the contribution of dust particles from comets to the zodiacal cloud is likely to be underestimated. Dust particles of cometary origin are indeed, while their spiral towards the Sun under Poynting-Roberstson drag, most likely to suffer some evaporation of dark carbonaceous compounds, as well as some collisions, and thus to get more compact and comparable to particles of asteroidal origin. Finally, Nesvorny et al. (2010) estimate that the inner zodiacal cloud was at least 10^4 times brighter during the Late Heavy Bombardment epoch and derive the amount of primitive dark dust material that could have accreted on terrestrial planets. Taking into account the characteristic structure (with irregular grains and fluffy aggregates) of the particles of cometary origin, as already pointed out in Levasseur-Regourd et al. (2006), we will now carefully investigate this critical topic.

4.3 Implication for Earth Delivery of Carbonaceous Compounds

The theory of meteoritic ablation during atmospheric entry, including the effects of thermal radiation, heat capacity and deceleration for solid particles, has been described in a number of publications (e.g. Jones and Kaiser, 1966). In general, the thermal equilibrium of the particle is given by:

$$\frac{1}{2}\Lambda\rho_a v_\infty{}^3 A_{proj} = A_{tot}\varepsilon\sigma_S\left(T_s^4 - T_e^4\right) + \frac{4}{3}\pi r^3 \rho_m c_s \frac{dT_m}{dt} \qquad (2)$$

where Λ is the heat transfer coefficient, ρ_a the density of the atmosphere, v_∞ the entry velocity of the particle, A_{proj} the projected surface of the particle, A_{tot} the total surface of the particle, ε the emissivity of the particle, σ_S the Stefan constant, T_s the surface temperature of the particle, T_e the environment temperature (atmosphere), r the equivalent radius of the particle (quantity for which $4\pi r^3/3$ equals the volume of the particle), ρ_m the density of the particle, c_s the specific heat of the meteoric substance, T_m the mean temperature of the particle, and t the time. This expression determines the relationship between the heat transfer from the atmospheric molecules to the particle and the light emission and heating of the particle.

As a first approximation, the transfer heat coefficient and the emissivity can be assumed to be equal to unity (Jones and Kaiser, 1966). Moreover, if the particle is small enough, typically with r less than tens of microns, then its temperature is always uniform (Murad, 2001) and the rightmost term of the equation (2) can be ignored. The equation (2) simplifies to:

$$\rho_{a1} \approx \xi \times \frac{\sigma_S T_b^4}{v_\infty{}^3} \qquad (3)$$

where $\xi = A_{tot}/A_{proj}$. In the case of spherical particles, $\xi = 4$, and assuming the evaporation temperature is about 2.1×10^3 K (Öpik, 1958), then evaporation of a particle that enters the atmosphere at 30 km s^{-1} starts at 101 km of altitude. Knowing that the ratio ξ can be 1.7 times higher for the case of typical spheroidal particles (oblate with a ratio of semi major axes of 2) and up to $\sim\pi$ for the case of aggregated fractal particles (Meakin and Donn 1988), this equation gives values for the altitude of evaporation of about 97 km and 93 km respectively for the same entry velocity.

However, the deceleration of the particle due to the collisions with the atmosphere molecules should also be taken into account. Assuming that the molecules stick to the particle and thus transmit all their momentum to the particle, the conservation of momentum implies:

$$v = v_\infty \exp\left[-\frac{3H\rho_a}{4R\rho_m \cos(\chi)}\right] \quad (4)$$

where H is the typical height of the atmosphere and χ the angle of the entry trajectory with respect to the zenith. Substituting this expression in equation (2) gives the expression for which the temperature obtained is maximal to be:

$$T_{\max}^4 = \frac{1}{\xi} \times \frac{4\Lambda R\rho_m v_\infty^3 \cos(\chi)}{18e\sigma_S \varepsilon H} \quad (5)$$

with e the natural base of logarithms. From this equation, the critical radius of the particles that can enter the atmosphere of Earth without being completely ablated can be determined. We have already seen that the shape parameter ξ can range from 4 for spherical particles to 4π for aggregated particles. The effect of the shape of the particles on the equilibrium temperature reached during atmospheric entry can be seen in Figure 4, assuming an entry velocity of 30 km s^{-1}. While the radius for which spherical particles reach the ground without being ablated is about 4.7 µm (Jones and Kaiser, 1966), the largest equivalent volume radius of irregularly shaped particles can reach up to 15 µm.

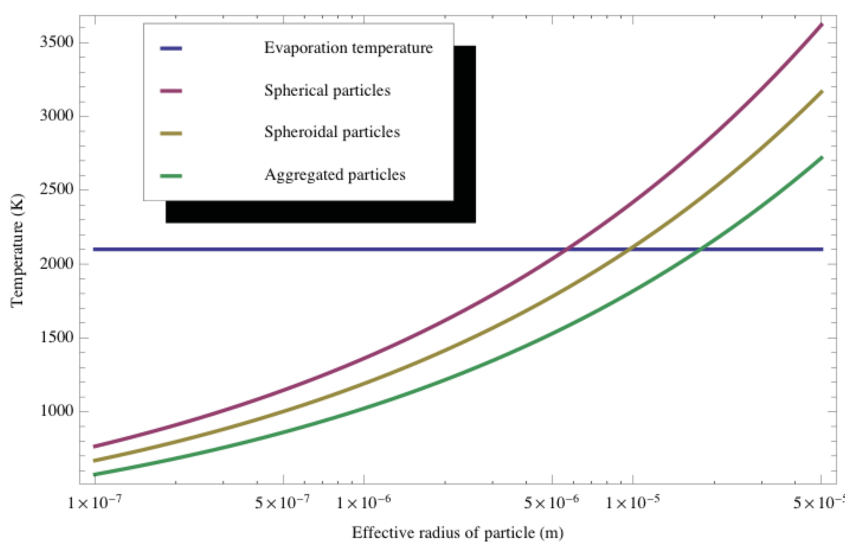

Figure 4. Maximum equilibrium temperatures for particles entering the Earth atmosphere at 30 km s^{-1}. The horizontal line corresponds to the temperature of sublimation of meteoritic materials suggested by Öpik (1958) of 2.1×10^3 K. The increase in size for the more efficiently decelerated particles (spheroids and aggregates) is obvious.

All parameters staying the same, irregularly shaped particles and fluffy aggregates can bring up to $\sim\pi^3$ more material in volume without being ablated to the Earth's surface than compact spherical particles. Cometary dust particles are therefore ideal candidates to bring carbonaceous compounds for seeding life on early Earth.

5 Conclusions

The long-standing controversy debated in the interplanetary dust community, around the relative contributions to the interplanetary dust cloud of dust resulting from asteroidal collisions and dust ejected by comet nuclei seems now about to be closed, with evidence for a major contribution of particles of cometary origin in the inner solar system and in the vicinity of the Earth, as established from their morphology (significant amount of aggregates), their composition (significant amount of organics) and their region of formation (inner solar system). It may thus be suggested that, not only meteor streams, but also sporadic meteors and micrometeorites, have mostly a cometary origin.

While more precise zodiacal observations are expected in a near future from Akatsuki spacecraft during its cruise between the Earth and Venus, a key implication of these conclusions is related to the early evolution of the solar system. During the LHB epoch, while the spatial density of dust in the interplanetary dust clouds was orders of magnitude greater than nowadays, the structure of dust particles originating from comets has quite likely favoured the survival of organics during their atmospheric entry.

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