DOI:10.1478/C1A0501001

Atti dell'Accademia Peloritana dei Pericolanti
Classe di Scienze Fisiche, Matematiche e Naturali
Vol. LXXXIII, C1A0501001 (2005)
Adunanza del 16 maggio 2005

EXPLORING THE DUSTY UNIVERSE

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(Nota presentata dal Socio Ordinario Paolo V. Giaquinta)

ABSTRACT. Dust is an ubiquitous inhabitant of the interstellar medium, and leaves an unmistakable signature in its optical properties, and physico-chemical evolution. Although there is little direct knowledge of the true nature of interstellar dust grains, strong evidences point toward the possibility that such grains are composites of many small monomers (mainly made of silicates and carbonaceous materials). We consider two different models of fluffy dust aggregates, occurring as result of ballistic particle-cluster and cluster-cluster aggregation, and a cluster with a Gaussian-like sphere size distribution. We study the optical properties of such composite structures through the multipole fields and the Transition Matrix approach. Our results show the severe limits of applicability of the effective medium theories. By comparing radiation and gravitational forces, we also infer some relevant insights into the dynamical evolution of composite grains in the Solar System. We finally explore the possible role of composite fluffy dust grains in igniting an extraterrestrial prebiotic chemistry.

1. Interstellar dust: An overview

The first observational evidence about the existence of "holes in the sky" appeared around 1784, thanks to the observations of William Hershel, musician and astronomer at the court of King George III. At that time, these holes were interpreted as due to the absence of stars. Now we know that they rather indicate the presence of "something" in the interstellar space, capable of absorbing starlight [1]. Figure 1 shows how these characteristic "holes in the sky" (now known to be dense interstellar clouds) look like. Then, what is this "something"? The main agents responsible for the observed darkening effect are dust grains whose size is comparable with the wavelength of visible light. These particles absorb and scatter starlight, i.e. extinguish it. In the interstellar clouds the dust particles are well mixed to the gas, contributing approximately 1% of the overall mass of material. Dust grains play a crucial role in the thermal balance of interstellar clouds, in many chemical reactions, in the collapse of interstellar clouds in the process of star formation, and in the formation of planets.

FIGURE 1. The “Black Cloud” B68. Permission to reproduce the figure was granted by ESO, which holds the copyright. Taken from web site http://antwrp.gsfc.nasa.gov/apod/ap990511.html

Doubtless, cosmic dust consists of several components [2]. They are typical of the special environments in which they are formed and/or decisively modified. Models of interstellar dust must take into account a variety of observational constraints on composition and morphology. Detailed information about dust chemical composition can be obtained evaluating what is missing from the interstellar gas, that is the “depletions” from an assumed standard stellar composition. The study of the interstellar extinction represents the most traditional and still efficient approach to obtain information about morphology, size and chemical composition of dust. The interstellar extinction curve is mainly characterized by a rise from the infrared through the visible into the ultraviolet, with a bump appearing, with surprising constancy, near 220 nm [3, 4]. Many scientists in the past decades have been dealing with the explanation of this ubiquitous feature which seems to be due to a plasma oscillation in crystalline graphite. However, the question remains still open, since there are too many free parameters in the description of the problem and so it is not of an easy and unique solution. Observing how the extinction varies with wavelength, it is possible to deduce some basic parameters of interstellar dust. It is made up mainly of particles of carbon and of silicates, with a size distribution ranging from a few nanometers to a size comparable with the wavelength of visible light. Most models assume a cut-off in grain size at around one or two microns. The proposed size distributions are frequently in

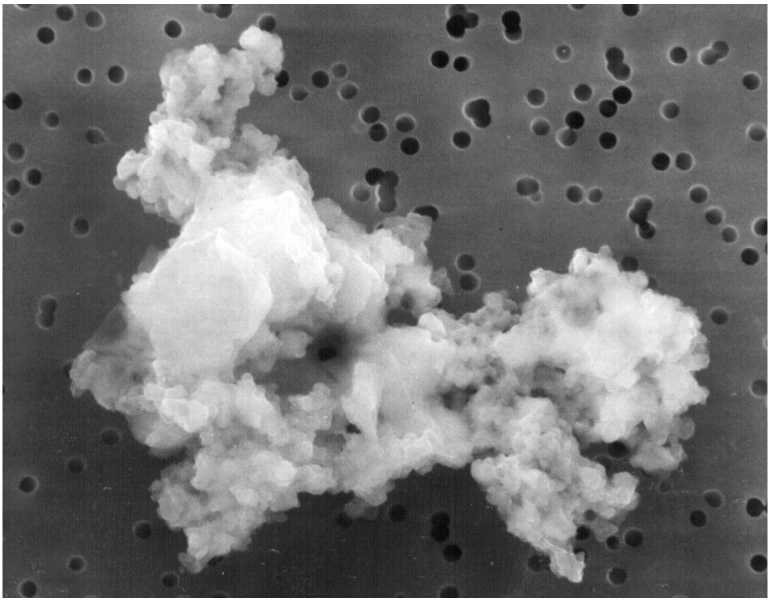

FIGURE 2. A $10\,\mu\mathrm{m}$ interplanetary dust particle known as a Brownlee particle. Acknowledgement is made to NASA for allowing reproduction of this picture from web site http://stardust.jpl.nasa.gov/science/sci2.html

the form of an inverse power law for the grain size, which means that there are very many smaller grains than large.

Together with the starlight extinction processes, there are some other relevant observational evidences pointing towards the existence of interstellar dust. Let us for example think of the reddening of stellar light. It is due to the differential extinction induced by dusty clouds. The obscuration of a star is always more pronounced for blue light than for red and this makes all stars seen through a dust cloud appear somewhat redder than they should. Starlight is often a few percent linearly polarized, thus suggesting a selective extinction very likely due to dust grains, partially aligned by some interstellar magnetic fields. Interesting infrared emission features also appear that can be explained in terms of re-emission processes of light previously absorbed by the grains in the visible-ultraviolet. In this sense, infrared spectroscopy turned out to be one of the most powerful and informative approach to the study of interstellar dust. Absorption by amorphous and crystalline silicates, molecular ices including water, carbon dioxide, carbon monoxide, and methanol has been identified [5]. The Infrared Space Observatory (ISO)- a European satellite- recently allowed very accurate measurements to be performed. Warm dust shows a spectral emission in the near to mid-infrared characteristic of polycyclic aromatic hydrocarbons (PAHs) [6]. However, individual PAHs have not yet been identified.

Another relevant source of information is obtained by collecting interplanetary dust as it falls into the Earth. Generally, this dust underwent many physical processes during its path to our planet, but still contains an unmodified component. Bradley and co-workers identified glasses with embedded metals and sulfides (GEMS), that look very much like what we expect interstellar dust to be [7]. Figure 2 shows quite an impressive picture of an interplanetary dust particle collected in the stratosphere.

A crucial point in the interstellar dust modelling concerns the investigation of dust grain morphology. For many years, for obvious technical difficulties connected with the computational capabilities available at that time, interstellar dust grains have been modelled as spheres. These models were quite unrealistic, when we think of the complicated mechanisms leading to the formation and growth of dust in the interstellar medium. We now reasonably assume dust grains to appear as non-spherical complex particles, resulting from the aggregation of smaller sub-units, leading to highly irregularly shaped, porous, fluffy, and even fractal structures. It is likely that dust grains appear as core-mantle (i.e. stratified) particles made of a core of dielectric materials (specifically silicates) covered with organic mantles of carbon. Since the dust usually is very cold (typically about 10 K), molecules tend to stick when they collide with grain mantles, and icy mantles accumulate on them, that can be detected by IR spectroscopy. Another molecule detected to be present in the icy mantles is CO. Substantial amounts of oxygen, carbon, and nitrogen are also locked up in grain mantles. Grain surfaces offer a quite active and interesting chemical scenario, providing surfaces where hydrogen atoms can recombine to form H_2 molecules [8]. This reaction is the initial step in all of interstellar chemistry [9].

It is quite fascinating and instructive to try to picture a scenario for the formation of interstellar dust.*"Once a galaxy has formed and stars begin to burn their fuel, i.e. hydrogen, then the ashes of those thermonuclear processes begin to acccumulate. These ashes, principally in the form of carbon, nitrogen, and oxygen are ultimately returned to interstellar space in stellar winds or in supernovae explosions. There, they are incorporated in the gas which forms the next generation of stars. The Earth and all its inhabitants are made of these ashes. The atoms of which each of us is made were at one time in the interior of a star more massive than the Sun"* [9]. In each year, a mass about 30 000 times the mass of the Sun is injected into the interstellar space of our Galaxy in the form of dust. The lifetime of the dust grains responsible for the interstellar extinction curve is estimated to be about 500 million years, which is just a few percent of the age of the Galaxy. The main destruction mechanisms of dust are represented by shocks, via sputtering or shattering.

It is widely accepted that interstellar dust in space changes its intimate nature through different evolutionary phases. For instance, the various forms of amorphous carbon, especially polymeric, graphitic, and diamond-like carbon can under suitable conditions be readily converted from one to another. Irradiation by UV of H-rich polymeric carbon reduces the H-content and lowers the bandgap energy making the material appear more graphitic, increasing the absorption in the visible, and causing luminescence in the infrared. Conversely, the exposure of graphitic carbon to hot H atoms can reverse the process [10]. These processes, which have been extensively explored in the laboratory [11, 12], also suggest the intriguing possibility of following the time evolution in the interstellar extinction curve [13].

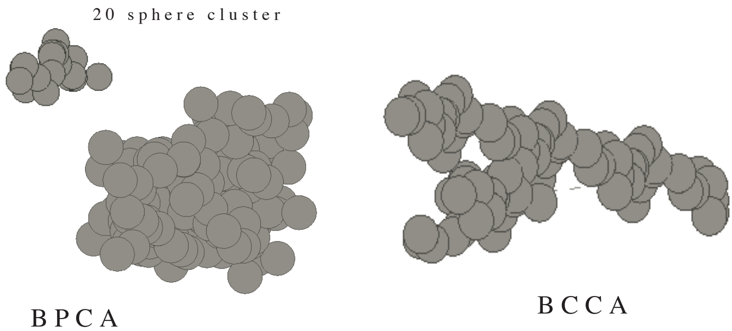

FIGURE 3. Geometry of the 200 sphere BPCA and BCCA aggregates. The starting cluster of 20 spheres is also shown.

2. Optical properties and morphological analysys

A correct interpretation of the nature of interstellar dust depends on our ability to propose models able to reproduce the observed optical behaviour, and at the same time consistent with the elemental abundance constraints in the interstellar medium [14, 15, 16]. The bulk of observational data may so be interpreted in a self-consistent scenario which correlates optical behaviour to structural properties of dust.

Some authors propose models for the interstellar dust in which the bulk of the infrared, visual, and ultraviolet extinction arises from composite, core-mantle, and multilayered grains with varying degree of porosity [17, 18]. However, the computational approaches commonly adopted in the literature show severe limits in treating rigorously the scattering and absorption of light by such particles, since, to overcome computational difficulties, effective medium theories (EMTs) are often used. EMTs unfortunately involve heavy approximations on the dielectric functions which may be not completely justified [19]. Moreover, when the optical properties of a composite particles are studied by means of EMTs, material interfaces and shapes are smeared out into a homogeneous average mixture.

More sophisticated approaches rely on a finite element method, e.g. the Discrete Dipole Approximation (DDA) [20, 21], in which the scattering particle is approximated by a regular array of N point dipoles of known polarizability tensor. The main drawback of the DDA is the fact that, to obtain a reliable approximation of the scattering power of the particle, a large number of dipoles, $N \approx 10^4$, must be used. The calculation must be repeated for each direction of incidence because no simple relation exists between the orientation of the particle (with respect to the incident field) and the scattered field. As a consequence, when averages over the orientation of the particles are needed, the computational effort may become unsustainable. Other computational approaches go through the use of statistical techniques, e.g. the Strong Permittivity Fluctuation Theory [22] and exact methods [23, 24].

We introduced, for the first time in the context of astrophysical literature [25], a computational technique which had been extensively applied to the study of atmospheric aerosols.

Both aerosols and interstellar medium are dispersions of anisotropic particles within a homogeneous medium. This similarity validates the applicability to the interstellar medium of methods and techniques that were originally devised for terrestrial/atmospheric studies. We use the vector multipole field expansion of the electromagnetic field in the framework of the Transition Matrix (T-Matrix) approach [26] which can give results with an arbitrary accuracy. This technique was developed by Borghese and co-workers in the past decades [24]. The T-Matrix has well defined transformation properties under rotation that permit a straightforward (analytical) evaluation of orientational averages [24, 27]. As a consequence, the T-Matrix approach presents invaluable advantages when dealing with the properties of dispersions of particles whose orientational distribution is known. In fact, as we are interested in the optical properties of dispersions as a whole, we exploit these properties assuming a random orientational distribution. The analytical evaluation of the averages produces a much improved accuracy of the solution and results in a remarkable reduction of CPU time. In the simple case of a random orientational distribution, Mishchenko & Mackowski [28] estimate the CPU time needed for the analytical evaluation of the orientational averages to be a factor of thousands shorter than that required by a numerical evaluation.

Moreover, the T-Matrix approach provides a compact and elegant formalism suitable for dealing with scatterers of (almost) arbitrary morphology [24]. Thanks to its flexibility, we applied it to many different dust grain models: porous (eventually coated) grains, modelled as spheres containing several spherical inclusions of vacuum [25]; clusters of spheres [29]; fluffy fractal aggregates [30]. We do not go here into the mathematical details of the technique that can be found in [24], but rather focus on the discussion of some interesting results obtained for models of aggregated grains.

The formation of aggregates by coagulation has been discussed extensively [31, 32, 33, 34, 35], but still there is no direct observational evidence of the final result of the aggregation processes. Wurm and Schnaiter [36] argue against the existence of dust aggregates composed of a large number of monomers and suggest small clusters, up to $8 - 16$ monomers, as good candidates to explain some relevant observables. According to their calculations, big clusters fail to explain the observed polarization effects since the polarization induced by the special shape and orientation of a monomer is balanced by the polarization due to another monomer with opposite orientation. On the other hand, theoretical expectations exist that coagulation is a very efficient mechanism for producing large aggregates composed of some hundreds or even thousands of sub-grains in regions with gas densities larger than a million hydrogen nuclei per cubic centimeter [31].

In our computations we adopt two different models of cluster growth: firstly via single particle aggregation and then through cluster-cluster aggregation [30]. In the first case, the aggregate is generated through subsequent sticking of single spherical monomers on the cluster surface, until we reach the final configuration shown in figure 3 and made of 200 monomers (Ballistic Particle-Cluster Aggregation, BPCA). In the case of Ballistic Cluster-Cluster Aggregation (BCCA) the building blocks are identical groups of 20 coalesced spheres (shown in the left top corner of figure 3) with an overall compact morphology. We assume that two of such groups move along straight trajectories, undergo collisions and stick together at their first contact point. We do not assume any dynamical model for particle coagulation. Instead the overall process is driven by a random number generator

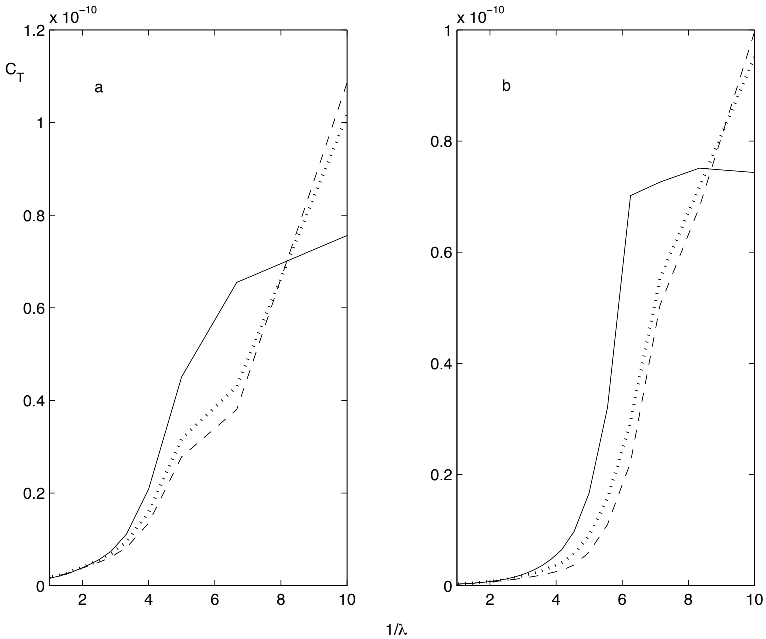

FIGURE 4. Extinction cross sections (in cm^2) for BPCA aggregate (dotted line), BCCA aggregate (dashed line), and corresponding equivalent mass sphere (solid line). Grains are made of amorphous carbon (a), and silicates (b). $1/\lambda$ in $\mu\mathrm{m}^{-1}$.

in order to build unbiased morphological patterns. We assume that the monomers, forming both BPCA and BCCA clusters, have identical radii of 5 nm. Resulting BPCA clusters have somewhat more compact structures with respect to BCCA clusters that are highly asymmetric. The fractal dimension [37] is $D = 2.3$ for the BPCA cluster, $D = 1.5$ for the BCCA cluster. Since we are using a relatively small number of spheres $N \leq 200$, we do not reach the fractal limit for either cluster models.

The convergence criterion that we use throughout the calculation [38] has been carefully checked for the above clusters [30]. We perform analytical averages over the orientations of the scatterers assuming, in all cases, a random distribution of the orientations. We investigate the effects of the aggregation, using as grain constituents either astronomical silicates [40] or amorphous carbon [41].

Figure 4 shows that the equivalent mass sphere is in general comparable, if not more efficient, in extinguishing radiation than aggregates, at least in the visible-ultraviolet spectral range. This is a direct consequence of the smaller size of the equivalent sphere, which approaches closer the dimension of the wavelength of the incident radiation. These results suggest that the presence of aggregation cannot give a larger extinction cross section per unit mass, with respect to the homogeneous sphere, as inferred in previous calculations based on EMT [17]. Figure 4 also shows that the extinction cross sections appear to be

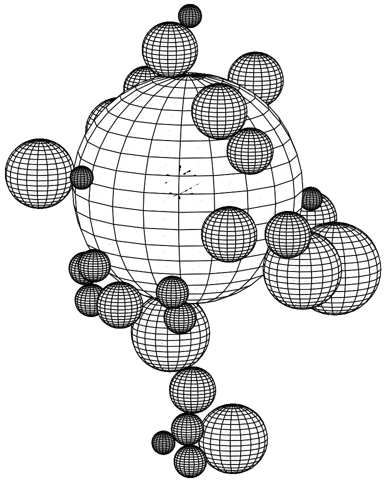

FIGURE 5. Geometry of the cluster with a Gaussian-like sphere size distribution.

only slightly dependent on the shape of the aggregates. This behaviour is reproduced independently of the number of constituent monomers for both BPCA and BCCA aggregates [30]. This imply that it is not so instructive to go too much into morphological details. Although this result appears to be sufficient robust, caution must be applied in extending this conclusion to different models!

We also studied the optical properties of cosmic dust grains modelled as aggregates of spherical sub-units with different radii [42]. Figure 5 shows the reference model: a grain aggregate composed by a large coagulation center (with radius 50 nm) and 31 coalesced spherical monomers (characterized by a Gaussian size distribution, with radii ranging from 5 up to 20 nm). Figure 6 shows the extinction cross-sections per unit mass for silicate clusters, comparing the initial (coagulation center alone) and final (cluster fig. 5) stages of coagulation. We observe a sharp increase in the effective extinction over the whole spectral range (a factor of four, roughly). Particle clustering induces multiple scattering processes that lead to the enhancement of the extinction properties. In the UV region, i.e. when the sizes of the coagulated particles are comparable to the radiation wavelength, cluster extinction cross-sections present morphologically induced features that are remarkably different from the optical behaviour of the homogeneous sphere. Increasing the wavelength (see panel b in fig. 6), the morphology plays a minor role, even if the cluster extinction cross-section keeps off-setting from that of the coagulation center. Grain shaping of larger units (i.e. the coagulation centers) during the aggregation process tunes the optical properties of dust clusters inducing a significant increase in the "efficiency" of scattering per unit mass.

By the end, is clustering synonymous of enhanced extinction power? From the above results, it follows that the answer to this question is related to size parameters of both aggregate and constituent subunits. As a consequence there are no general recipes. What we can surely state is that the presence of aggregation produces detectable changes in the scatterer optical signature, making its optical properties strongly different from those of the

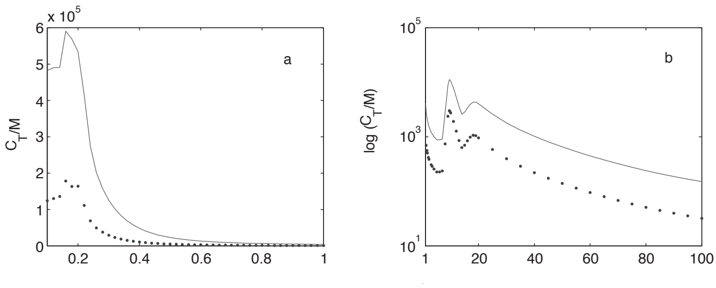

FIGURE 6. Extinction cross section normalized to the mass $(\mathrm{cm}^2/\mathrm{g})$ as a function of $\lambda\,(\mu\mathrm{m})$ for silicate grains. The dotted line refers to the coagulation center, the solid line refers to the whole cluster of Fig. 5.

homogeneous equal mass-sphere, and this rules out definitely the applicability of EMTs to composite particles.

3. Dynamical behaviour

A number of papers have been devoted to assessing the forces acting on dust grains resulting from radiation, gravity, gas-drag, and galactic magnetic fields [44, 45, 46, 47]. For an ensemble of identical particles whose orientational distribution is assumed to be known, the average of the radiation pressure force, $F_{\rm pr}$, reads as

$$\langle F_{\rm pr}\rangle = \frac{I}{c}\left[\langle \mathrm{C_T}\rangle - \langle \mathrm{g}\rangle\langle \mathrm{C_S}\rangle\right] = \frac{I}{c}\langle \mathrm{C_{pr}}\rangle \tag{1}$$

where the angular brackets denote orientational average, I is the incident intensity, c is the speed of light, g is the asymmetry parameter, $\mathrm{C_T}$, $\mathrm{C_S}$ and $\mathrm{C_{pr}}$ are the extinction, scattering and radiation pressure cross sections, respectively. Thus, a good knowledge of the optical properties of dust particles is important for a good understanding of their dynamical evolution.

An important parameter in determining the dynamical evolution of dust is the colour of the radiation source. To quantify the effects induced by differences in chemical composition and morphology of clusters, we compute the ratio β between radiation pressure forces and gravitational forces in the case of a stellar radiation source [48]

$$\beta = \frac{K}{m}\int_o^\infty \lambda^{-5}\langle \mathrm{C_{pr}}(\lambda)\rangle \left\{\exp\left(\frac{hc}{\lambda k T_{\rm eff}}\right) - 1\right\}^{-1} \mathrm{d}\lambda \tag{2}$$

with

$$K = \frac{2\pi h c R_\star^2}{G M_\star}$$

where $R_\star$ and $M_\star$ are the radius and the mass of the star. The stellar spectrum is approximated by the spectrum of a black body at an effective temperature $T_{\rm eff}$. G is the gravitational constant, h is the Planck constant, k is the Boltzmann constant, and m the grain mass.

TABLE 1. β for the silicate (sil) and amorphous carbon (ac) cluster sequence shown in Fig.3

		20 spheres	200 spheres
sil	(BPCA)	0.10	0.14
sil	(BCCA)	0.10	0.12
ac	(BPCA)	1.09	1.26
ac	(BCCA)	1.09	1.18

The β values are used to characterize the dynamical behaviour of non charged, non magnetic dust particles in the Solar System or in optically thin circumstellar dust disks [49]. These are the conditions we are assuming hereafter. In a thick circumstellar disk several other processes become important, as the attenuation of stellar light, and the gas-drag effect. Computed β values for the cluster configurations in figure 3 are shown in Table 1 for the circumsolar radiation field. Morphological effects are indeed significant only for the solar-type star, because of the coincidence of the peak blackbody temperature with the largest differences in the cross-sections of the adopted cluster configurations. The results shown in table 1 suggest that aggregates consisting of silicates are confined in the solar system because $\beta < 1$. Fluffy carbon aggregates show values of $\beta > 1$ for either cluster configurations. Even for the individual amorphous carbon monomers (with radius 5 nm), β approaches 1 ($\beta = 0.96$). The values of the ratio β of the radiation to the gravitational forces show that there is no removal of dielectric grains (silicates) from the solar system. On the contrary, absorbing carbon grains are very likely to be moved by the radiation pressure forces against the gravity acting on them. The inertial response to radiation forces of highly porous aggregates tends to become similar to that of constituent particles, and β becomes independent of the aggregate size [48, 39].

Beyond the customary radiation pressure, that is the component of the radiation force along the direction of incidence of the incoming wave, we also computed the components of the radiation force in a plane orthogonal to the direction of incidence (transverse components)[43]. For non spherical particles such components do not vanish. Our calculations showed that, although the transverse components are generally smaller than the radiation pressure, they are in no way negligible and may be important for some applications, e.g. when studying the dynamics of cosmic dust grains, as has recently been recognized by Klačka and Kocifai [50]. We also calculated the ensemble average of the components of the radiation force over the orientations of the particles in two physically significant cases: the case of random distribution, and the case in which the orientations are randomly distributed around an axis fixed in space (axial average). As expected, we found that, unlike the case of random orientation, the transverse components do not vanish for axial average. This could be important in the physics of cosmic dust when, for instance, a galactic magnetic field may produce an alignment.

4. Interstellar dust and bioastronomy

In the previous sections we have been dealing with models of fluffy dust aggregates, occurring as the result of ballistic collisions. The products of these processes are loosely packed structures with much of their internal volume being vacuum (cavities). This internal volume leads to a completely different chemical scenario with respect to the one occurring on the grain surfaces [51]. In the interior of dust aggregates UV radiation, X-rays, cosmic rays, thermal shocks, etc., induce a secondary chemistry where the reaction products cannot escape the cavity. This gives rise to a peculiar situation as chemistry is offered high-temperature, high-density and reducing conditions in a transient gas phase with rapid quenching of the reaction products. Since even a small amount of UV radiation has decisive chemical consequences on the molecular content of the cavity, a knowledge of the radiation density distribution inside an interstellar aggregate becomes essential.

We calculated the UV radiation density distribution inside the aggregate cavity through the usual approach, based on the multipole expansion of the electromagnetic field, and assuming the grains to be fluffily substructured collections of dust particles covered by ice mantles, loosely attached to one another. We found that a significant fraction of the energy of the impinging wave is found throughout the interiors of grains [52]. Thus, if an aggregate grain is exposed to large radiation fields for enough time, the inner ice mixture may become enriched of a significant number of radicals. After a collision or a cosmic ray impact, radicals and molecules from the ice enter a transient, warm, high pressure gas phase [53]. In this picture, cavities inside grain aggregates, filled with interstellar ices, become micro-reactors where stellar high energy photons and particles can ignite a chemistry in planetary-like physical conditions. The reaction products stored inside grain aggregates would also be partly shielded from the extremely unfavorable environmental conditions of the early evolutionary stages of the Sun [54].

The existence of an efficient biochemistry proceeding in the interior of dust grains during the early stages of the solar system formation has implications for the origin of life. Indeed dust grains might contain the right environment where the organic matter formed and survived in space, but also be the conveyor vehicles able to seed planetary systems with the prebiotic molecules needed for the synthesis of proteins and nucleic acids in living organisms. Instead of the search for new mechanisms of production of biomolecules, the focus of this study, currently in progress, is on the special *habitat* provided by the interior of interstellar grains.

The working hypothesis that we are attempting to validate is that in the cavities inside interstellar grains the formation of biomolecules occurs through well tested processes, i.e. radical chemistry in a reducing environment. Any theory of extra-terrestrial origin of life has to meet with some relevant observational constraints: (i) isotope ratios in amino acid and carboxylic acid extracts from the Murchison meteorite [55]; (ii) harsh external conditions [56]; (iii) non racemic mixtures of amino acids in carbonaceous meteorites [57].

In particular, item (iii) is related to the origin of homochirality, that is one-handedness, of amino acids and sugars, so far an unfilled gap for the theories of the chemical origin of life. Why amino acids occurring in proteins are, almost exclusively, of L-conformation and only D-conformation sugars enter the RNA and DNA molecules is, in fact, still an open and very crucial question. The difficulties intrinsic to any Earth-based explanation of the enantiomeric asymmetry of life suggest an extraterrestrial origin of the biomolecular homochirality [58], supported by many evidences. Among these are the discovery in the Murchison meteorite of more than 70 amino acids, eight of them occurring in proteins [59], and the discovery of a variety of sugars, in amounts comparable to amino acids, in the Murchison and Murray meteorites [60]. These findings seem to push the problem of the origin of biological chirality out into the cosmos.

Several controversial theories have been developed to explain an abiogenic origin of the chiral homogeneity in terms of the physico-chemical processes involved. Among the many scenarios proposed, one involves the asymmetric photolysis of amino acids present in space, triggered by circularly polarized ultraviolet radiation (Bailey 2001, and references therein). Many mechanisms have been proposed for the production of UV circularly polarized light (CPL) by astronomical sources [61], but none of them gives convincing results. We propose a new scenario in which amino acids formed in the cavities of interstellar aggregates are exposed to asymmetric photolysis induced by an effective UV CPL generated *in situ*. To this aim, we develop the multipole field formalism to explore the electromagnetic field polarization state in the interiors of aggregated structures [62]. The most general state of polarization of an electromagnetic field is elliptic and the direction of propagation is given by the Poynting vector $\vec{S}$. The latter has a fixed direction for a plane homogeneous wave and/or for a scattered field in the far zone. In both these cases the plane of the polarization ellipse is orthogonal to the Poynting vector, so that the state of polarization is conveniently described by the Stokes parameters constructed with the components of the field orthogonal to the direction of propagation [63]. In the interstitial material and in the cavities of the aggregate the direction of propagation of the field changes from point to point [64]. The plane of the polarization ellipse is in general not orthogonal to the vector $\vec{S}$. Consequently, the state of polarization of the field cannot be described by the usual Stokes parameters but it needs a more general description [65] e.g. through the definition of the real vector $\vec{V} = i\vec{E} \times \vec{E}^{\star}$, where $\vec{E}$ is the electric field and $\vec{E}^{\star}$ is its complex conjugate. The magnitude of $\vec{V}$ is $2/\pi$ times the area of the polarization ellipse. When $\vec{V} = 0$ the field is linearly polarized, otherwise the electric field rotates, as a function of time, in a counterclockwise sense with respect to $\vec{V}$. As a consequence, the sign of the quantity $V_S = \vec{V} \cdot \vec{S}/|\vec{S}|$ gives the sense of field rotation with respect to the direction of propagation of the electromagnetic energy and its magnitude is related to the extent of the depolarization. Details on the generalized description of the polarization of electromagnetic waves can be found in [66].

We approximate the aggregate with a simple model consisting of a homogeneous sphere with radius ρ_o embedding a spherical cavity with radius ρ_c. The incident field is assumed to propagate along the z axis and the reference plane is chosen to be the $x-z$ plane (Fig.7). The location of the embedded cavity is determined by the couple of polar angles θ_c and ϕ_c, and by the distance from the center of the host sphere. We show the results for a host spheres with $\rho_o = 100$ nm, and a cavity with $\rho_c = 74$ nm (40 % in volume). We choose four candidates for the interstitial material: (i) silicates [67]; (ii) amorphous carbon [68]; (iii) water ice [69]; (iv) a Bruggeman mixture of 30 % silicates, 30 % amorphous carbon and 40 % water ice. The Bruggeman mixing rule is applied only to the interstitial material, whereas the cavity is treated as a separate entity.

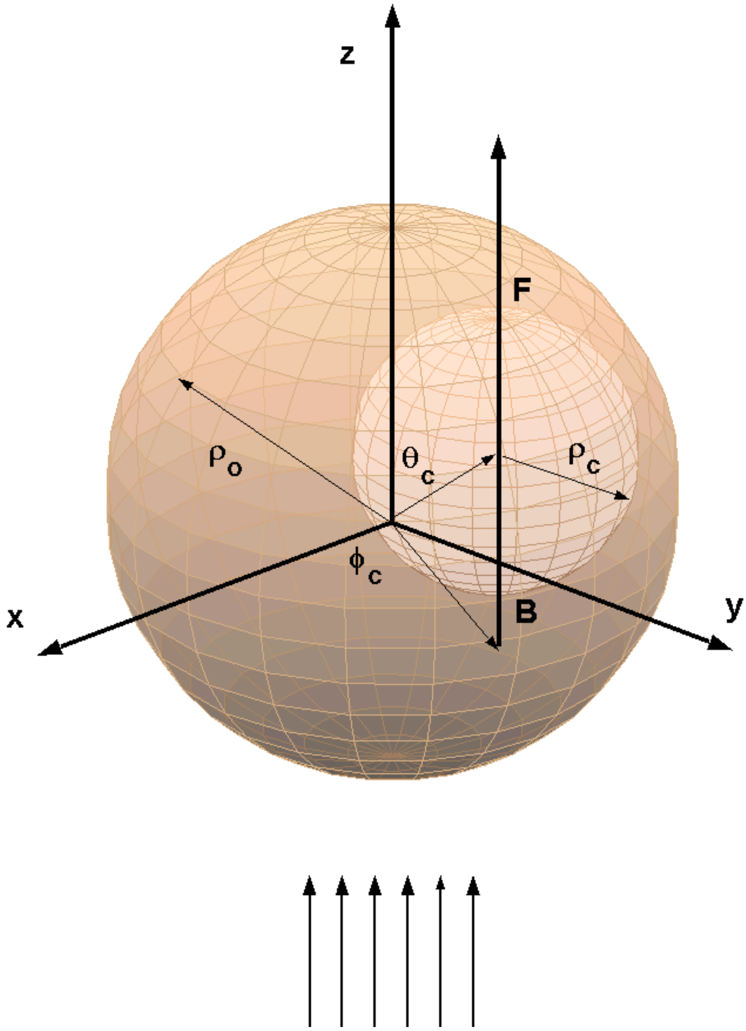

FIGURE 7. Geometry of the interaction between the impinging wave and the model particle.

We calculated V_S at B and F (cf. Fig.7), i.e. the points at which the parallel to the z axis through the center of the cavity crosses its surface. In the calculations we considered several locations of the cavity inside the host sphere. However, results are reported for a cavity tangent to the surface of the host sphere with the polar angles $\theta_c = 60°$ and $\phi_c = 30°$. This geometrical configuration gives a large depolarization effect. Calculations show that, rotating the position of the cavity with respect to both the x and y axes, the sign of V_S is unchanged. Of course, the magnitude of V_S depends on the particular location of the cavity. In order to explore to what extent the depolarization depends on the refractive index

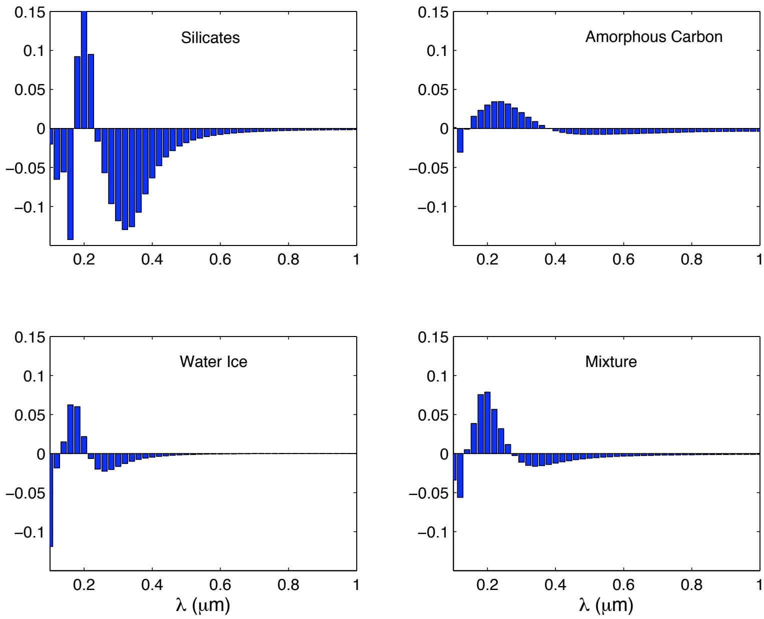

FIGURE 8. V_S, calculated at point F of Fig.7, as a function of the radiation wavelength for different materials. The sign of V_S gives the sense of rotation of the electric field. The radii of the host sphere and of the cavity are 100 nm and 74 nm (40% in volume), respectively.

of the interstitial material, in Figs.8 we show V_S calculated at point F as a function of the radiation wavelength for silicate, amorphous carbon, water ice and the Bruggeman mixture, and for a polarization of the incident field along the x axis. The depolarization appears to be almost independent of the refractive index, the maximum value of V_S occurring in the range $0.1 - 0.5$ μm for any choice of the material. Furthermore, no depolarization occurs above 1 μm. Hereafter we will consider only cases in which the refractive index of the interstitial material is given by the Bruggeman mixing rule, case (iv). Similar results are obtained at point B.

The scenario we propose is consistent with many of the relevant observational constraints. Since the ice mixture trapped in the interiors of dust aggregates is reminiscent of the deuterium fractionation characteristic of the cold interstellar chemistry, deuterium enrichment of metoritic amino acids is a logical consequence of the photochemistry of already enriched low temperature ices. Indeed, given that water in Murchison was probably deuterium depleted, forming deuterium enriched amino acids by the parent body acqueous chemistry appears higly unlikely. The cavities are a relatively "quiet" environment shielded from the harsh external ambient conditions. The electromagnetic radiation emitted by the central star undergoes depolarization in the interiors of coagulated grains providing a source of CPL. The induced polarization presents an alternation in the sense of rotation of the field that agrees signficantly with the CD spectra of non aliphatic amino acids (cf. fig.

8). If our scenario is valid, the apparent inconsistency of the mechanism of asymmetric photolysis in cases like Proline and Tryptophan [70] is dismissed. Finally, the ubiquitous mutual presence of UV linearly polarized radiation and some degree of dust aggregation in star-forming regions provides the conditions for a widespread universal replication of the chiral selection.

The enantiomeric excess of chiral biomolecules produced and protected in the cavities of grain aggregates contributed the source material that inseminated the Earth during the time of its formation and afterwards via comets and meteorites infall, making it possible for life to emerge.

5. Aknowledgments

We thank Prof. Santi Aiello for his constant support, and Prof. David A. Williams for his trust and for his always inspiring insight into the physics and chemistry of the interstellar medium.

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Presented: May 16, 2005
Published on line on November 23, 2005