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Measurement of dust properties in different Solar System environments

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Abstract. The interplanetary medium is populated by dust that mainly derives from comets and asteroids, the most primitive bodies of our Solar System. Moreover, a not negligible fraction of interstellar grains cross the interplanetary medium. To study comets and asteroids in situ is a major goal of present programs devoted to understand origin and evolution of the Solar System. To this aim the ESA Rosetta mission will visit comet 67P/Churyumov–Gerasimenko for more than one year, with a complex of instruments on the orbiter and a lander equipped for in situ analyses. A complementary approach to study our origins is to collect and bring back to Earth samples to be deeply studied in laboratory. NASA Stardust and Japanese Hayabusa missions will return cometary and astroidal matter, respectively. Other opportunities to get interplanetary and interstellar grains are given by long term exposure of collectors on the International Space Station and/or by collection of grains floating in the Earth stratosphere. In all these projects, a fundamental step is the deep and careful analysis of the collected samples in laboratory in order to characterise the actual nature of materials. We envisage that a combined effort along these lines will bring us to a better understanding of our Solar System.

Key words. Solar System: Interplanetary Dust – Laboratory: Experiments

1. Introduction

It is well known that materials in interstellar medium experience a continuous cycling from diffuse to dense clouds (Whittet 1992). Physical conditions, such as mass and density of dust and gas, control the formation of new stars and the origin of solar systems like ours. Internal nuclear reactions drive evolution of stars, until they expel material in quiet (red giants) or violent (novae and supernovae) events.

In this context, the analysis of primordial material preserved in our Solar System is essential to understand the formation mechanisms and the correlations with the interstellar matter, to study the evolution processes of the solar system bodies and to analyse the initial conditions and the chemical evolution towards life origin.

According to the commonly accepted formation theories, comets and – to a minor extent – asteroids are reservoirs of the primordial material from which the Solar System was formed 4.5×10^9 years ago.

Comets are “fragments” that have spent most of their time far away from the Sun and, thus, have had little interaction with energetic processes due to Sun activity. The Oort cloud extends above 30,000 AU from the Sun

Send offprint requests to: L. Colangeli and could contain 1,000 billion comets in randomly oriented orbits, while the Kuiper belt is a reservoir of up to one billion comets, positioned outside the Pluto orbit, between 30 and 1,000 AU. Actually, different comet "families" formed at different distances from the Sun and may have incorporated material coming from both the inner and the outer regions of the proto–solar nebula, in a mixture of primordial and partially processed compounds (Nuth et al. 2000). Asteroids are mostly concentrated in a belt between Mars and Jupiter, where the gravitational field of Jupiter prevented their aggregation in an additional planet.

The interplanetary medium is populated by several kinds of small natural grains: the Interplanetary Dust Particles (IDPs). They derive from material ejected by comets or asteroids. Cometary IDPs are still arranged in showers along the parent comet orbit, while an isotropic background is present, due to nowadays dispersed (due to the Poynting–Robertson drag) old showers.

It is a rather recent finding the identification of a not negligible population of interstellar dust (ISD) in the interplanetary medium. Dust monitoring experiments onboard Galileo and Ulysses space missions (Baguhl et al. 1995) have clearly shown that interstellar grains transit in the Solar System, as this moves through the local galactic environment. ISD grains have mass in the $10^{-11} - 10^{-7} g$ range, but the actual distribution is unknown. The estimated cumulative mass flux is about $10^{-4} s^{-1} m^{-2}$ for $10^{-15} g$ grains and $10^{-5} s^{-1} m^{-2}$ for $10^{-12} g$ grains (Landgraf & Grün 1998), about a factor 1/10 with respect to IDPs. Thus, there is a good chance to study directly chemical composition, mass amount and size distribution of real interstellar grains in our Solar System, an important information complementary to indirect data derived from astronomical observations.

Based on the previous discussion, to study properties of dust in our Solar System may provide a wealth of important information on the origin and evolution of materials from which our Solar System originated, as well as on real interstellar dust.

2. Exploration methods of primordial dust properties in the Solar System

The new frontier of dust exploration in our Solar System is based on missions and instrumentation aimed at performing in situ analyses and/or to collect and return samples to Earth for laboratory studies. Along this line move some ambitious space missions aimed at visiting primordial bodies. On the other hand, the fact that the trajectory of the Earth crosses the flux of IDPs and ISD allows us to monitor/collect natural particles on or in the neighbour of our planet.

Probably the most ambitious mission to visit a primordial body is the ESA Rosetta mission, presently flying towards the target comet 67P/Churyumov–Gerasimenko. Among other experiments for in situ measurements, three are dedicated to collect complementary information on dust ejected in the coma by the nucleus, during its approach to the Sun. COSIMA (Cometary Secondary Ion Mass Analyser – PI: J. Kissel) is aimed at studying the composition of single grains collected while the Rosetta orbiter will cross the comet coma; GIADA (Grain Impact Analyser and Dust Accumulator – PI: L. Colangeli) will measure the evolution in time of the flux of grains coming from different directions, the dynamics (e.g., velocity) of the dust in the coma, the mass of each collected grain, as well as the dust mass and size distribution (see Figure 1); MIDAS (Micro–Imaging Dust Analysis System PI: W. Riedler) will perform microscopic analysis of collected grains to determine morphology and aggregation status. It is also worth noting that Rosetta shall deliver a lander on the comet nucleus, aimed at measuring the physical and chemical properties of surface and sub–surface materials.

While Rosetta mission is designed to perform a long lasting in situ monitoring of its target comet, the NASA Stardust mission (Brownlee et al. 1997; Tsou et al. 2000) has a different approach. On January 2, 2004, Stardust performed a fly–by through the coma of comet 81P/Wild 2, to collect dust in passive aerogel collectors and to return them to Earth for analyses in laboratory. During the interplanetary flight some of the aerogel col-

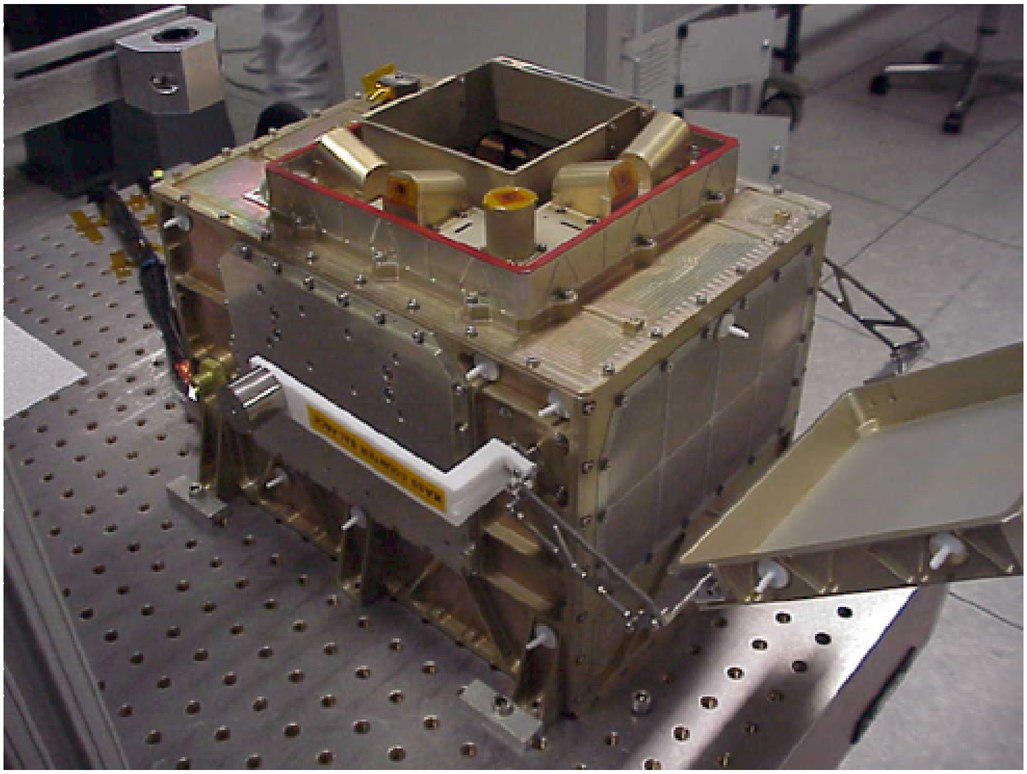

Fig. 1. The GIADA experiment with cover open during final tests. The main entrance to collect grains and the five micro–balances to accumulate dust from different directions are clearly visible on the top panel (courtesy of Galileo Avionica).

lectors were exposed to catch interstellar dust, too. Stardust is expected to return to Earth at the beginning of 2006. A selected number of international experimental teams have been appointed by NASA to plan and then participate to the first 6 months of analyses on the samples. Among them, also the Cosmic Physics and Planetology Laboratory (CPPL) of INAF–OAC (Osservatorio Astronomico di Capodimonte) and "Parthenope" University in Naples have been selected for participation to analyses on collected dust.

In fact, the CPPL has developed experience in handling and characterisation of IDPs by participating to the French–Russian Perseus program with the Comet–99 project, for dust collection on board the Mir station during Nov. '98 – Apr. '99. In such a period it was foreseen that the Mir station had to cross the Leonid meteor stream, linked to the orbit of comet 55P/Temple–Tuttle. The CPPL provided two 9.5 x 5.0 cm^2 aerogel collectors for grain capture (see Figure 2). Aerogel is an innovative material, formed by silica at very low (0.005 $g\ cm^{-3}$) density, that guarantees survival of impacting grains even at high (some tens $m\ s^{-1}$) speed. A typical trace of grain in the retrieved aerogel is shown in Figure 3.

For the future, the Japanese Hayabusa mission shall return samples collected from the surface of an asteroid for laboratory investigations on Earth.

In addition to space missions for direct dust sampling from primitive objects, our planet can be used as a sort of "collection facility" of IDPs. In fact, as mentioned above, the Earth crosses the trajectory of interplanetary and interstellar particles travelling through

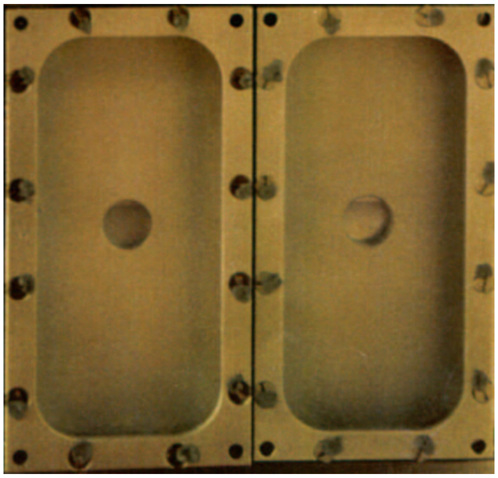

Fig. 2. The 2 aerogel collectors (9.5 x 5.0 cm^2 in size each) exposed for grain capture on the Mir station.

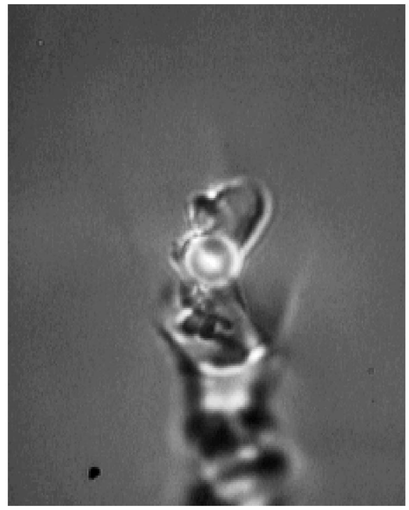

Fig. 3. FESEM image of an IDP trace in aerogel (spherical grain size: about 15 μm).

the interplanetary medium. Their collection is, then, possible either in the Earth stratosphere or from around the planet, e.g. from the International Space Station (ISS).

Regular NASA stratospheric flights (altitude 20 km) of aircraft equipped with sticky collectors under their wings allow the collection of a variety of such particles. The DUSTER (Dust from the Upper Stratosphere Tracking Experiment and Return) experiment led by "Parthenope" University (PI: P. Palumbo), in collaboration with INAF–OAC and an international team, funds on an innovative concept in which collection of dust is performed onboard stratospheric ballons with an active collection system. The main characteristic is that gas and dust are drag through a one–stage impactor device by operating a pump during flight. Grains are trapped on a collection surface to be analysed in laboratory.

The DUSTER experiment is a precursor of the more complex MEDUSA (Martian Environmental DUst Systematic Analyser) experiment. MEDUSA (PI: L. Colangeli) is foreseen to fly on the ESA ExoMars mission. The purpose is to sample Martian atmospheric dust to perform in situ analyses about physical properties of dust dispersed in the atmosphere. As in DUSTER, dust is drag through a five–stages impactor. The first stage is equipped with an optical sensor to monitor passage of single grains larger that about 2 μm and an impact stage to detect their impact momentum. The following stages are designed to select particles in well defined size ranges (2 – 1, 1 – 0.4, 0.4 – 0.1, 0.1 - 0.05 μm) and are equipped with micro–balance sensors for the measurement of the accumulated dust in each size bin. By operating MEDUSA at different times of the day and all along the Marian year, dust abundance, size distribution and other grain physical properties can be derived, for the first time.

Finally, as mentioned above, the ISS offers a unique opportunity for long duration exposure for interplanetary dust collection. In this respect, the DARLING (Direct Analysis and Retrieval in Low earth orbit of INterplanetary Grains) experiment (PI: P. Palumbo) couples passive collection of dust in aerogel (for analysis in laboratory after retrieval) with active optical identification and timing of each impact event. The advantage of such combined approach is that, once returned to Earth, each sin-

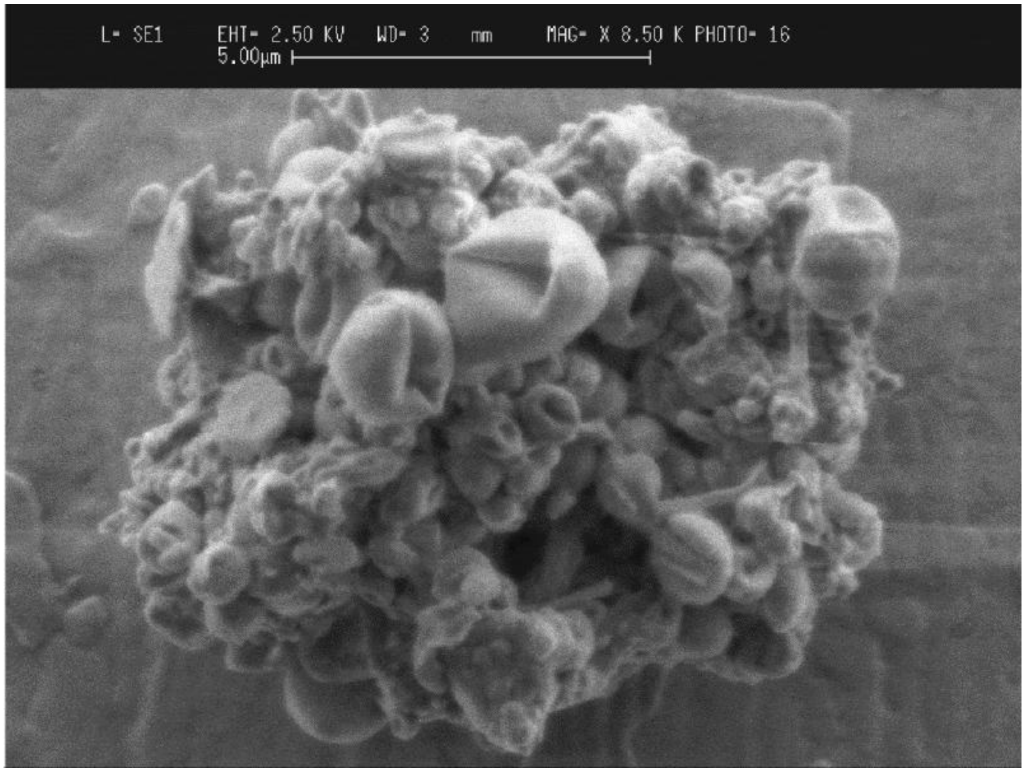

Fig. 4. FESEM image of an Interplanetary Dust Particle.

gle grain can be identified in position, direction and time of arrival. This is a great improvement with respect to previous purely passive collection experiments flown on the Mir (see above) as the new approach will allow us to discriminate "families" arriving from different directions and at different times, possibly constraining their origin, e.g. as cometary or interstellar. The DARLING experiment has been approved by ESA within the "Life and Physical Sciences and Applied Research Projects" for a possible flight as soon as the ISS access will be restored.

3. Methods for laboratory analysis

Based on the perspectives reported above, the future years will offer the chance to perform extensive analyses in laboratory on extraterrestrial samples, mainly in the form of very small grains. To actively participate to such effort, laboratories must be equipped with dedicated instrumentation and must have developed a specific know–how in the handling and characterisation of dust.

The CPPL in Naples has a long lasting experience in this field and has developed a basic equipment to perform specialised measurements on dust samples, as well as on single grains, that perfectly suite to the goals of characterisation of IDPs and ISD. Specific techniques for such a task available at CPPL are summarised here following.

Field Emission Scanning Electron Microscopy (FESEM) allows morphological characterisation of dust samples, as well as of single grains at spatial resolution about 2 nm. The result is a full morphological characterisation of the returned sample (e.g., the distribution of grains in the collection matrix) and the study of single grain morphology. The FESEM image of an IDP studied in our laboratory is shown in Figure 4.

The Energy Dispersive X-ray (EDX) analysis is a power tool to study quantitatively elemental composition and distribution of elements with Z > 3. By this method a clear identification of the composition and, thus, of the origin of the grains can be obtained.

IR micro–spectroscopy in the spectral range 600–5000 cm^{-1}, at spectral resolution 4 cm^{-1} and spatial resolution (spot size) 20–400 mm can be performed in transmission or reflectance (phase angle = 0^o) modes to study spectral fingerprints of collected single grains and, so, to characterize the chemical composition.

4. Conclusions and future needs

There are several approaches that contribute to study the origin of our Solar System. One way to get information about the primordial material from which it was born is to perform in situ measurements and/or to carry on measurements on samples originating from primordial bodies. Ambitious space missions such as Rosetta, Stardust and Hayabusa are targeted to these goals. Experiments in the stratosphere and/or from the ISS can provide additional samples to be analysed. In this context it is important that laboratories with qualified experimental equipments and experience in dust analyses join in a coordinated effort to exploit at best the samples provided by these programs.

It is clear, however, that in the frame of the international competitions, experimental teams must be supported by their national organisations in order to maintain the available instrumentation, periodically update the experimental set-ups and have the possibility to involve young researchers to whom transfer know–how.

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