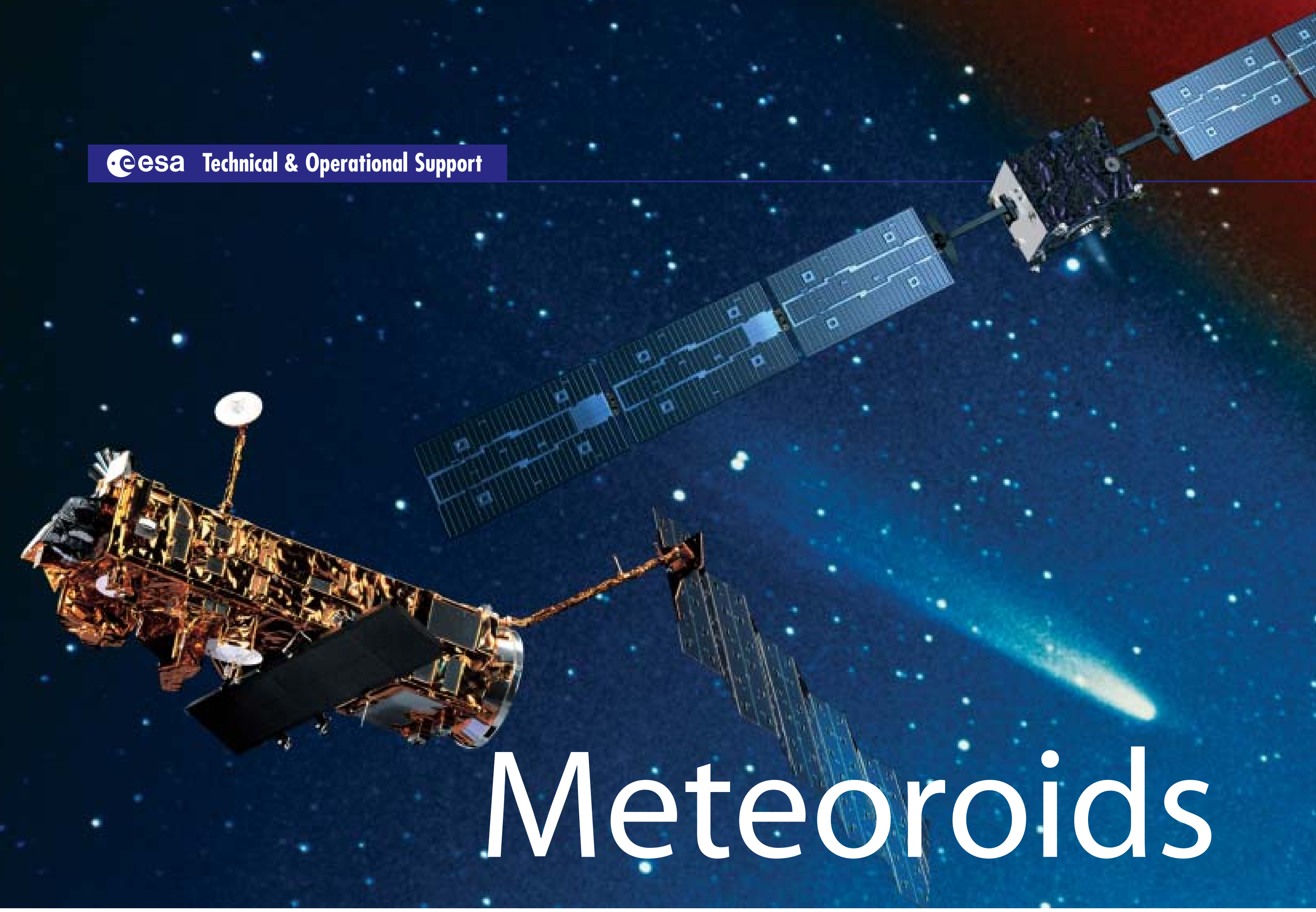


Meteoroids

– A Potential Hazard for Interplanetary and Earth-Orbiting Spacecraft

Markus Landgraf, Ruediger Jehn & Walter Flury
Mission Analysis Office, ESA Directorate for Technical and Operational Support, ESOC, Darmstadt, Germany

Valeri Dikarev & Eberhard Grün
Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Introduction

Meteoroids, the millimetre-sized particles that cause the spectacular streaks of light that regularly zip across the night sky, can seriously damage interplanetary as well as Earth-orbiting spacecraft. Therefore, as ESA builds up its fleet of research and applications spacecraft in orbit, it is prudent to assess the risk posed to these space missions by a potential meteoroid strike.

Interplanetary missions like Rosetta and Mars Express will encounter a meteoroid environment that is quite different from the one that we know from near-Earth space. However, observations of meteors, astronomical measurements, and detectors on earlier interplanetary spacecraft have given us much of the data needed to predict the risk of colliding with a meteoroid. The ESA Meteoroid Model contains these measurements as a database, and links these data points with a physical model of the distribution of meteoroids in the Solar System. Quantifying the risk in this manner takes us half of the way to avoiding it!

Meteoroids – Travellers in Interplanetary Space

Interplanetary space is pervaded by meteoroids more than a tenth of a millimetre across, with an average of one such particle in every 500 cubic kilometres of space at the Earth's distance from the Sun (which averages 149 597 900 km and is defined as 1 Astronomical Unit or AU).

Sporadic (non-streaming) meteoroids constitute the bulk of the particulate matter in interplanetary space. They are spread over vast regions, stretching from the close vicinity of the Sun to the Kuiper Belt and beyond. Meteoroids are being continually shed from the asteroids and comets of our Solar System as these collide with each other and as the Sun evaporates their volatile components. The most dramatic large-scale producers of meteoroids are the active comets like Halley and Hale-Bopp. Their visible dust tails consist mostly of micron- (one thousandth of a millimetre) sized grains that leave the Solar System quickly on hyperbolic trajectories. Most of the mass lost by comets and asteroids, however, goes into grains with sizes of between one tenth of a millimetre and one millimetre, which are not as visible. On the other hand, these grains are here to stay, and they orbit the Sun with enormous speeds - around 30 km/s in the case of a circular near-Earth orbit.

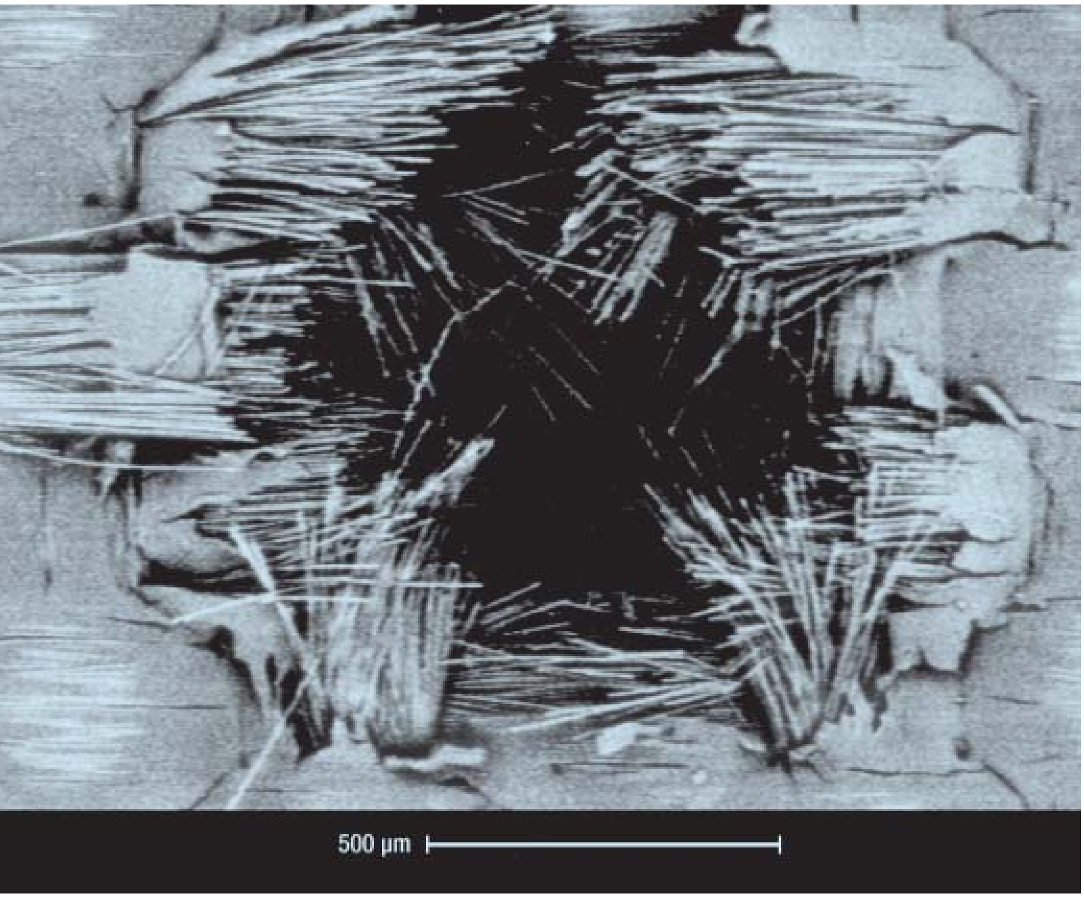
Our knowledge of the makeup of meteoroids has come mainly from the collection by high-flying aircraft of grains that have entered the Earth's atmosphere. They have a mainly stony composition, with the dominant minerals being the olivines and pyroxenes already known on Earth, but they also contain organic components. They therefore exhibit a wide range of material densities, with the average being 1 gram/cm^3. At typical encounter speeds above 30 000 km/h, a meteoroid of any density can cause considerable local damage.

Any object in space, be it a sophisticated weather satellite or an astronaut taking part in an EVA (Extra-Vehicular Activity), is exposed to the risk of a meteoroid impact. We therefore have to protect ourselves and our equipment from that risk by using shielding. But how much shielding is needed and how many meteoroids can we expect to hit our spacecraft? To answer these questions, a detailed study was performed at the Max-Planck Institute for Nuclear Physics in Heidelberg. The result is an updated version of the ESA Meteoroid Model, which provides us with reliable information on the meteoroid environment based on the latest available data and physical modelling.

The Meteoroid Hazard

How do we know that meteoroids damage spacecraft? One excellent source of proof is ESA's European Retrievable Carrier (Eureca), which was brought back to Earth by the Space Shuttle (flight STS-97) in 1993 after 10 months in low Earth orbit. From Eureca we know that meteoroid impacts cause structural damage as well as surface degradation. Serious structural damage occurs when relatively large meteoroids break essential parts of the spacecraft structure, for example struts and springs. Smaller meteoroids typically cause surface degradation by cratering the exposed surface and thus changing its optical and thermal properties.

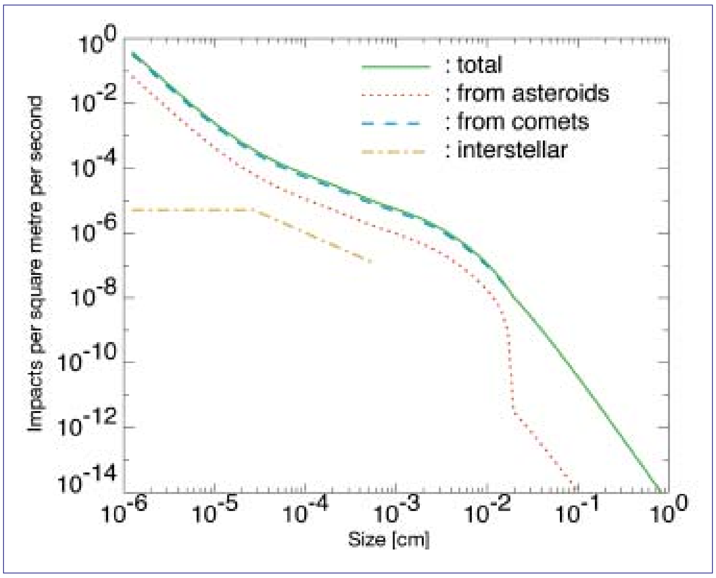
The accompanying photograph shows a piece of the betacloth blanket from Eureca that has been penetrated by a meteoroid. Betacloth is a composite material made of Teflon and fibreglass, which is normally used as a protection against meteoroid impacts. The projectile that penetrated it in this case was sufficiently fragmented by the impact that it could not penetrate much further into the spacecraft's structure. However, this example also shows that the integrity of protective layers will be degraded over time as more and more of the material is destroyed. Some recent minor damage to the X-ray detector of ESA's XMM telescope has also been linked to a possible meteoroid impact.



Hole in a betacloth blanket (Teflon-coated, woven fibreglass) from the European Retrievable Carrier (Eureca). The impact zone is highly irregular due to the structure of the material and there are signs of melting at the ends of the glass fibres

These examples demonstrate that understanding the meteoroid environment is not only important when designing spacecraft, but also for planning the operations of their scientific payloads. Optically active surfaces like the mirrors or lenses of cameras are extremely sensitive to surface degradation. They are also difficult to protect from meteoroid impacts because they need a free field of view for observation.

In addition to the direct effects of a meteoroid impact, there are also more subtle, indirect consequences. The highly energetic impact event creates a small cloud of charged particles, which can disturb electrical systems onboard the spacecraft. The failure of ESA's Olympus spacecraft on 11 August 1993 was attributed to such a disturbance. The failure of solar cells of the Hubble Space Telescope has also been linked to a discharge avalanche, which could have been started by a meteoroid impact.



Meteoroid environment of the Earth as a function of meteoroid diameter. The size distributions of meteoroids from three sources are shown: asteroids, comets, and the interstellar medium

Predicting the Risk

The ESA Meteoroid Model is a statistical model of meteoroids originating from comets and asteroids that is based on the physics of their release and distribution. It is constrained by data from ground-based observations as well as spacecraft data. It can be used to predict the rate at which meteoroids between one micrometre and a few centimetres in size can be expected to hit spacecraft travelling in the region of space between 0.1 and 10 AU from the Sun.

Since the number of such meteoroids is so enormous – there are of the order of 10^{25} particles larger than 1 micron between the orbits of Venus and Mars – a statistical description of their distribution in space and velocity can be used. However, this statistical description is only as good as the data that constrains it, most of which is from Earth-bound observations. Observations of meteors in the night sky are important because the meteoroids involved in their formation are a few millimetres in size, the same size range that can be dangerous for spacecraft. Fainter meteors, which are caused by meteoroids less than a millimetre across, can be detected by radars. In addition to the meteor observations themselves, an important source of data are astronomical observations of the heat radiated by the meteoroids in space.

As the data obtained from Earth-bound measurements do not provide the full picture of the meteoroid population, data from detectors onboard interplanetary spacecraft like Ulysses have also to be used to constrain the model predictions. However, all of the available data still covers only a relatively short period of time and a small fraction of interplanetary space. To predict the risk for future missions, therefore, we need an underpinning physical model of the distribution in our Solar System of meteoroids produced by two mechanisms: close encounters with massive planets, and so-called Poynting-Robertson drag. Close encounters with giant planets affect mainly large meteoroids, Jupiter's strong gravity field being particularly efficient in dramatically changing their orbits. Poynting-Robertson drag is a much more subtle physical phenomenon, caused by the asymmetric re-emission of sunlight by the meteoroids. Over tens of thousands of years, it makes the meteoroids spiral in towards the Sun. This means that here on Earth we can expect meteoroids originating from the asteroid belt between Mars and Jupiter, as well as from comets that circle the Sun outside the Earth's orbit.

Equipped both with the data on meteoroids in interplanetary space and the physical model of their distribution mechanisms, the ESA Meteoroid Model is well-suited to predicting the risk to any spacecraft mission venturing into the Solar System between 0.1 and 10 AU.

The Risk to ESA Missions

Whilst any space mission is at risk from meteoroids, missions on long transfer trajectories are especially vulnerable. ESA's Mars Express and Rosetta scientific missions are good examples in this respect. Both will be flying close to the ecliptic plane of the planets from the Earth outwards. While Mars Express will be exposed to meteoroids spiralling in from the asteroid belt as well as cometary grains, Rosetta will be exposed mostly to grains from comets or even more remote and exotic sources like the Kuiper Belt and the Interstellar Medium. Earth-orbiting spacecraft, on the other hand, are mainly exposed to cometary meteoroids, as can be seen in the accompanying figure.

The ESA Meteoroid Model allows us to assess the risk for Mars Express and Rosetta. Because these missions will be crossing interplanetary space, the meteoroid environment will change as they progress. The accompanying diagrams show the rate (impacts per square metre per second) of impacts on the spacecraft along the transfer trajectory of two sizes of meteoroids: relatively large ones of 1 mm diameter and much smaller ones of 1 micron. In both cases, the impacts of small meteoroids are more than one million times more frequent than those of large meteoroids.

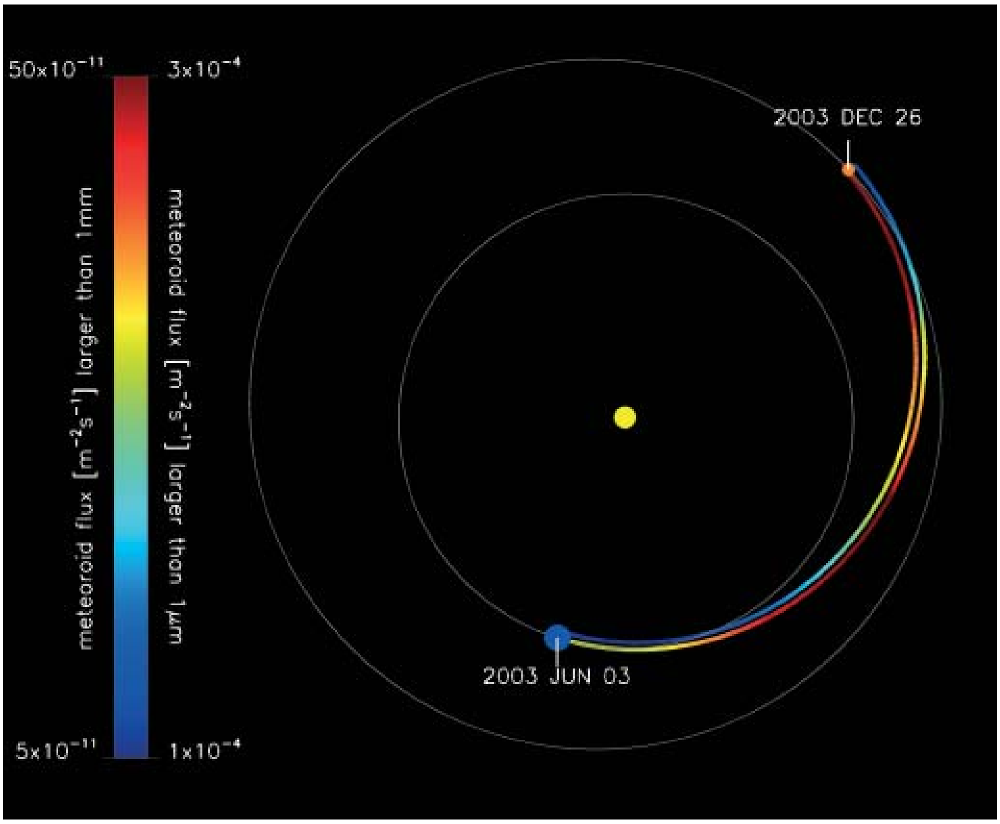
In the case of Mars Express it can be seen that, while the flux of small meteoroids decreases as the spacecraft journies further away from the Sun, the flux of large meteoroids increases. This can be explained by the large concentration of small meteoroids close to the Sun. This concentration also creates what is called the 'false sunset' or zodiacal light, which is the light reflected off small meteoroids close to the Sun that can sometimes be seen after sunset with the naked eye. These small meteoroids mainly affect the solar panels which, with their 11 m^2 surface area, will suffer 100 micron-sized-meteoroid impacts every day. This high number of impacts does not put the spacecraft at risk, however, due to the small size of the impacting particles. It is the 1 mm sized particles that can seriously damage the spacecraft, but they are so much rarer that there is only a 3% chance of such a particle hitting the 3 m^2 body of the spacecraft. There is, however, about a 10% chance that a mm-sized meteoroid will penetrate its solar panels. The flux of mm-sized particles will actually increase as the spacecraft approaches Mars, because the dynamics of large meteoroids cause them to stay close to their parent bodies - in this case the asteroids of the Main Belt, which lies just beyond the orbit of Mars.

Conclusion

We know from hardware brought back earlier from space that the risk faced by spacecraft from meteoroids is real. The heavily pitted surfaces of Eureca and the shattered solar cells of the Hubble Space Telescope bear witnesses to the harsh meteoroid environment in Earth orbit. From measurements in interplanetary space, we know that there too one has to expect meteoroid impacts, but luckily the most prolific meteoroids are very small and the bigger ones much less abundant. Nevertheless, when designing a mission it is important to consider the meteoroid environment in which the spacecraft will actually fly and special care needs to be taken for missions that will cross the asteroid belt, where the number of millimetre-sized meteoroids is expected to be much higher.

Both Mars Express and Rosetta have just a few percent probability of being damaged by a millimetre-sized meteoroid. Future ESA missions will fly into very different meteoroid environments. The mission BepiColombo mission to Mercury, for example, can expect to encounter a very large number of small meteoroids, as these are concentrated close to the Sun. Other scientific missions like LISA and Darwin will spend a long time in interplanetary space and must therefore also be carefully analysed for meteoroid impact risk.

If we design our spacecraft properly using the environmental models available at ESA, we can fly safely in interplanetary space. Then we can enjoy the more pleasant consequences of meteoroids in the form of zodiacal light or the light shows that they bring to our skies when the Earth passes through the orbital path of a comet.



Meteoroid flux (impacts per square metre per second) on the Mars Express spacecraft from its launch on 23 June to Mars orbit insertion on 26 December 2003. The inner colour-code shows the flux of 1 mm meteoroids (left side of the colour-scale), and the outer one that of 1 micron meteoroids (right side of the colour-scale).