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Degradation of Space Exposed Surfaces by Hypervelocity Dust Bombardment – Example: Solar Cell Samples

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1. Introduction

The analysis of cosmic particles by secondary ion mass spectrometry (SIMS) has developed into an essential tool of cosmophysics and –chemistry as well as of applied space-research. This way it is feasible to gain important information about the origin, the evolution and the structure of our solar system (Brownlee, 1978; Grün et al., 2001). In addition, the discrimination between terrestrial and cosmic particles is critical for an estimate of damage of space exposed surfaces by the impact of such particles. This is especially important for the multitude of satellites in near-earth space, i.e. in low earth orbits, fig.1.

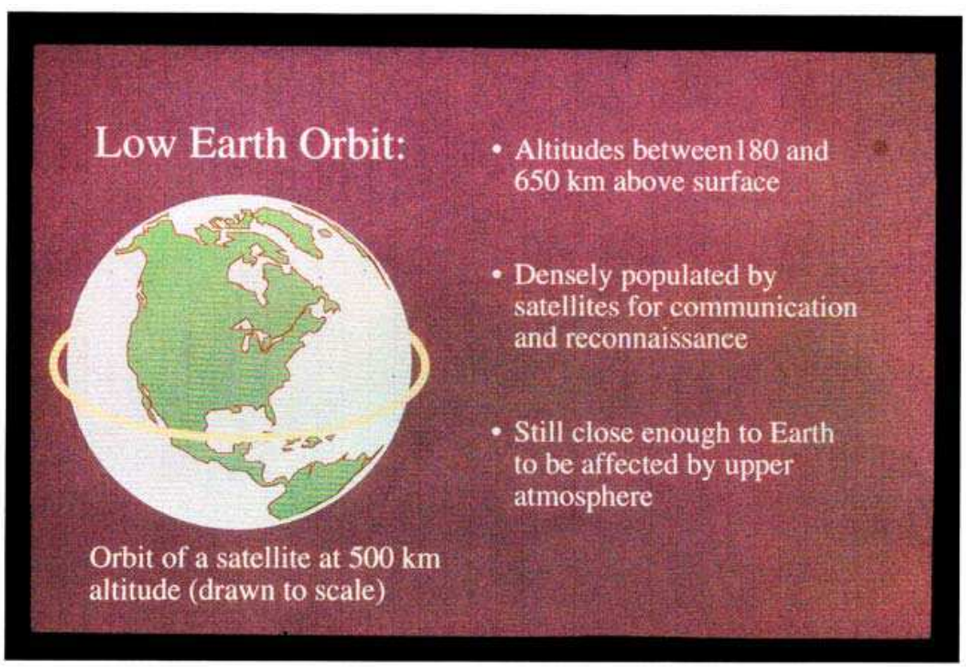


Fig. 1. Draft of a satellite orbit in 500 km altitude

Low earth orbits (LEO), i. e. the altitude between 180 and 650 kilometers above the earth's surface, is one of the busiest traffic zones in space. Nevertheless, the conditions in LEO are harsh. It is a region of intensive hard UV-radiation and the little oxygen still present from the earth's atmosphere is highly-reactive atomic oxygen. It is also a region of high temperature variations between -100°C to +100°C and, as will be discussed in more detail later, a region full of manmade space debris –in addition to cosmic dust micrometeorites (Murr & Kinard, 1993)

Particles are travelling there with velocities of around 10 km/s. If they hit material surfaces they almost completely evaporate due to their high impact velocity and cause the formation of a crater, which is up to one order of magnitude larger than the impacting particle, fig.2.

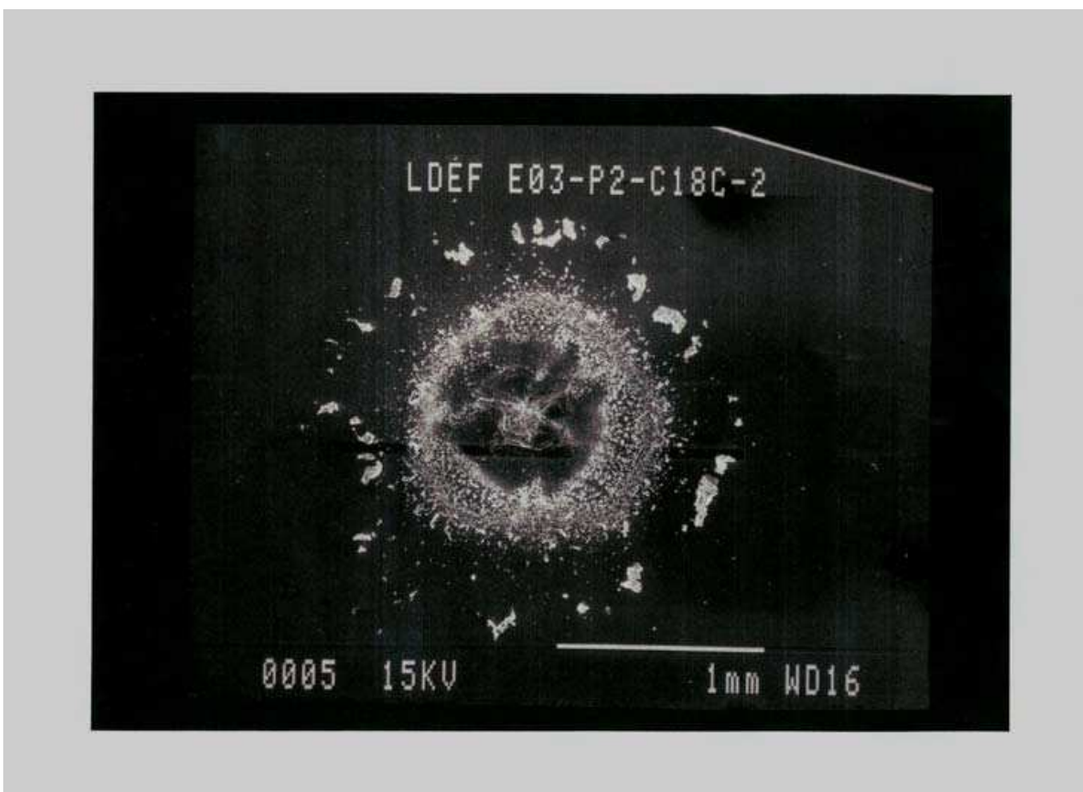


Fig. 2. SEM-micrograph of an impact crater on a germanium surface caused by a cosmic dust particle. In order to clearly differentiate between ions generated from material and such of the impacted particle in SIMS-analysis, it is advantageous to use rather exotic and highly pure substrates such as gold or germanium. The particles scattered around the impact crater are Ge-particles and not remnants of the impacted cosmic particle which evaporated completely. Only extreme traces of its matter are detectable by SIMS.

This turns out to be a serious problem for space technology because the impact of a multitude of such particles will quickly deteriorate space exposed surfaces. The mean life time e.g. of solar panels for the generation of energy for satellites is thus seriously reduced.

2. Cosmic dust: An essential part of matter in the universe

The investigation of cosmic dust particles has thus developed to an interesting and fascinating area of cosmophysics and –chemistry (Stadermann, 1992). Cosmic dust constitutes an essential part of matter in the universe. The earliest hint of the existence of dust in our solar system came from the observation of the zodiacal light. This can be observed with bare eye shortly before sunrise or shortly after sunset, over the Eastern or Western horizon, respectively. Already in the 18th century, Cassini interpreted this Zodiacal light as light-reflection and – scatter caused by a giant cloud of dust particles in the ecliptic. Today, it is known from spectroscopic investigations of the reflected sun light that these dust particles have diameters between 0.1 and 100 µm. The zodiacal dust cloud exhibits the form of a flat disk and extends over the whole inner range of the solar system.

From theoretical considerations it is known that the dust particles of this cloud do not move on Kepler-orbits around the sun but instead move on spiral orbits into the sun (Stadermann, 1992). This "Poynting-Robertson -Effect" is caused by a retardation of orbiting particles by an interaction with the solar radiation. For a 10 µm particle the life time is limited to about 100,000 years before it is burned up in the sun. Some are also trapped by the earth's gravity and may enter its atmosphere. Cosmic particles up to about 50 µm can efficiently radiate away the heat which is generated by their slowing down in the earth's atmosphere due to friction. Greater particles cannot do this effectively enough and hence, burn up in the upper layers of the atmosphere. This leads to the apparent paradox that microscopic dust particles as well as meteorites as big as one's fist survive the entrance into the earth's atmosphere while particles of the size of a grain of sand burn as shooting stars. The macroscopic meteorites survive their travel through the atmosphere because of a totally different reason: They fall so quickly that their inner part does not heat up while only their outer layers evaporate. Once decelerated from cosmic velocities, the cosmic dust particles which are of prime interest to us take a long time for their trip from the earth's outer atmosphere to the earth's surface: depending on atmospheric conditions (wind, weather) this part of their trip can last several months. They usually endure this travel relatively sound and this is the reason why our planet is daily gaining several tons due to the trapping of extraterrestrial material (Stadermann, 1992). This gain in part is counterbalanced by a loss of hydrogen, helium, atomic oxygen and possibly carbon (mainly as methane) in the exosphere as a result of non-thermal escape mechanisms (Shizgal & Arkos, 1996)

3. Problems with sampling of interplanetary dust

The seemingly simplest way – the direct collection of cosmic dust in space with a dedicated space exposed device is in practice rather problematic. The problem is the high velocity of several km/s with which these particles travel. If they hit a collecting device without deceleration they almost completely evaporate in fractions of a second. A part of the evaporated material will condense around the crater which is formed upon the particle impact while only a minor fraction of the original projectile will survive the impact as debris inside the crater, fig.2.

An ideal collector for cosmic dust particles would gently decelerate the often fragile particles. And this is exactly what happens in the outer realms of the earth's atmosphere. Eventually, the particles are sedimenting down with quite low velocities. Interestingly this also causes a density of cosmic particles in the earth's atmosphere that is many orders of

magnitude higher than in space. In order to prevent a mixing of cosmic particles with terrestrial aerosols the sampling has to be carried out in the stratosphere. In the 1960s it was tried to collect cosmic dust with high flying balloons. However, the yield was very modest. Therefore, NASA initiated a program in the 1970s in which cosmic dust was collected with U2-planes flying in the stratosphere (Stadermann 1992). For this purpose, palm sized collecting surfaces have been prepared which were coated with silicon oil. These collecting surfaces were exposed to the air stream of planes travelling at an altitude of 20 km (twice as high as most commercial traffic) beneath a wing of the plane for several hours. Nevertheless, only a single particle greater than 5 µm is caught per hour. Of these very few collected particles in the clean surrounding every second particle is still of terrestrial origin. Often ash particles from volcanic eruptions are found which had been injected into the stratosphere. Hence, after greater volcanic eruptions (as, e. g. of the Pinatubo in 1991) the collection of cosmic dust in the stratosphere has to be discontinued for several months because the volcanic dust cloud is dispersed quickly and thoroughly around the earth.

It goes without mentioning that during sample preparation and investigation no additional contamination can be tolerated, work has to be performed under strict cleanroom conditions and, due to the dust grain size, mostly under the microscope. Hence, particles are removed one by one from the collector surface and subsequently cleaned from the silicon oil. They are thereby viewed in the light microscope. Afterwards they are characterized closer in the scanning electron microscope (SEM). Fig. 3 shows some typical particle morphologies of extraterrestrial particles.

Modern new detection systems for hypervelocity microparticles using piezoelectric material have rather recently been developed (Miyachi et al., 2004). Furthermore, a dust cloud of Ganymede has also been detected by in situ measurements with the dust detector onboard the Galileo spacecraft (Krüger et al., 2000).

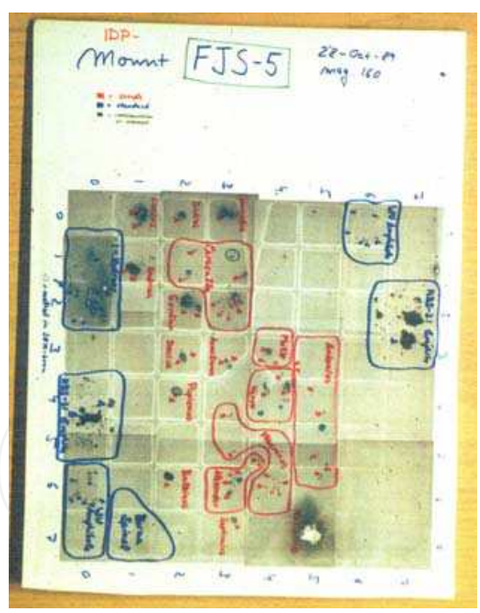
4. Secondary Ion Mass Spectrometry (SIMS) – the key instrumentation for cosmic dust analysis

It is difficult to gain information on the nature of impacting particles due to the fact that most of the particle matter is evaporating during the impact. The minute amounts of particle matter which remain on the material surface in and around the impact crater can only be detected by a very sensitive method of topochemical analysis. SIMS is the topochemical method with the highest detection sensitivity and, hence, it is the method of choice for such investigations. In addition, the ability of SIMS to distinguish between various isotopes of an element is the key to differentiate between terrestrial and cosmic particles (Stadermann, 1990). It has been observed in LEO that the most serious degradation is caused by terrestrial aluminium oxide particles (Corso, 1985). The origin of such particles was a solid rocket fuel (Al-powder) which was used by one of the nation's leading in space technology. It was finally feasible to ban this technology in favour of liquid fuels for rocket propulsion which do not generate Al_2O_3-particles. The outstanding significance of SIMS for such investigations consequently led to the development of the NanoSIMS (Schuhmacher et al., 1999) which exhibits a dramatically improved lateral resolution in the ten-nanometer domain (as compared to a lateral resolution in the single µm-range for a conventional SIMS instrument). It also has a multi-detection system which is important since the amount of material to be sputtered is very limited in this special application, fig.4.

3a. Spherical particle. Main elemental composition: Mg, Si, O (traces Ca, Fe).The morphology of the particle indicates that it once was in a realm where the temperature was higher than its melting temperature. Another possibility would be the emission from a melt.

3b. This particle seems to be a conglomerate of smaller particles. Main elemental components: Mg, O (N, C, H).

3c. Precipitate of an LDEF impact on germanium. The broad dark stripe is the trace of the ion beam with which the analysis was carried out.



3d. Particle storage sheet of Stadermann

Fig. 3. SEM-micrographs of some typical particle morphologies of extraterrestrial particles (Stadermann, 1990)

Fig. 4a shows the ion optical system of the NanoSIMS of CAMECA (Courtesy of CAMECA, Paris). Fig. 4b shows the NanoSIMS 50 installed in the laboratory of the Physics Dept. at Washington University in St. Louis

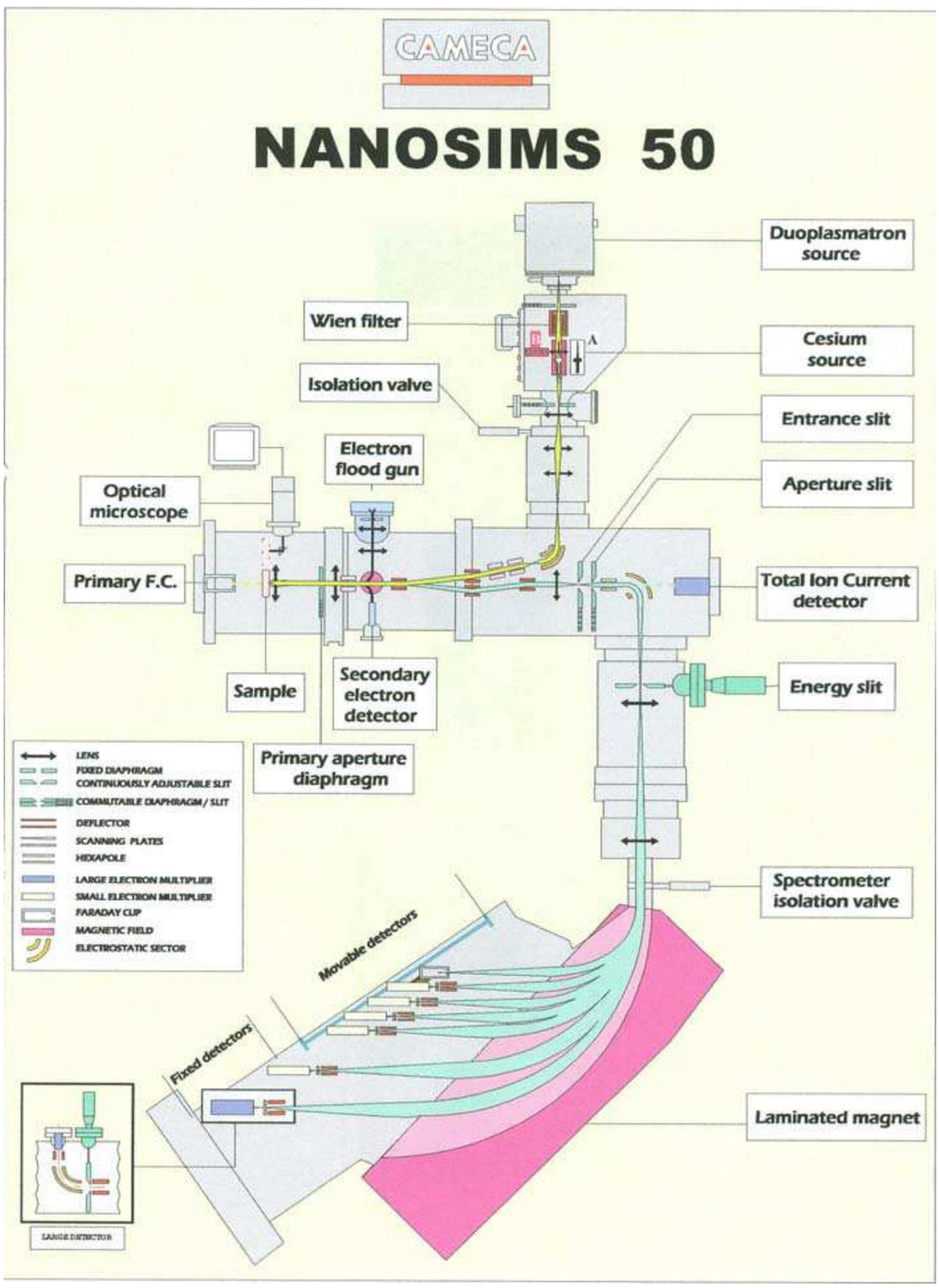


Fig. 4a. The NanoSIMS 50 of CAMECA (Courtesy of CAMECA, Paris)

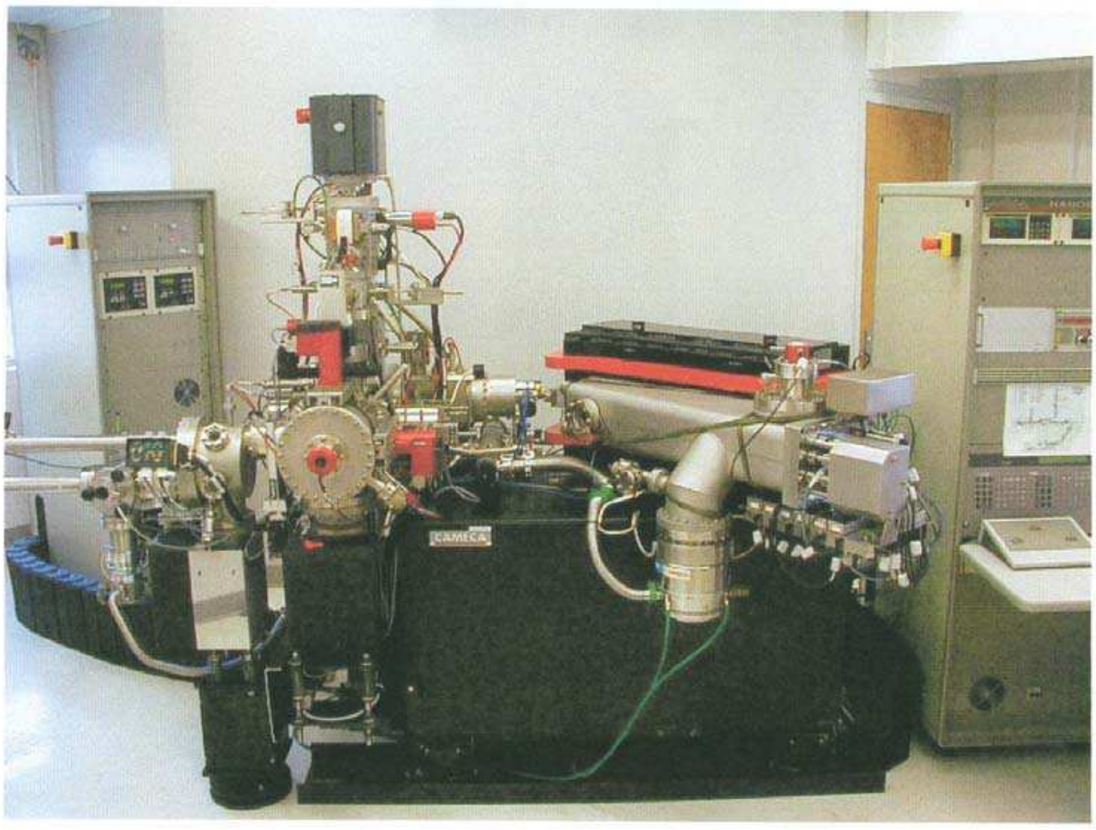


Fig. 4b. The NanoSIMS 50 in the laboratory of the Washington Univ., Physics Dept., St. Louis, MO, USA

The impact crater of fig. 2 demonstrates impressively how space exposed surfaces eventually deteriorate by impact of many such particles.

5. The significance of material degradation of space exposed surfaces – the LDEF experiment

This has alarmed the American National Aeronautics and Space Administration (NASA) to an extent that a respective materials degradation experiment was organized, the LDEF-experiment (Long Duration Exposure Facility). The heart of this action was a large cylindrical satellite with a length of 9 m which is shown in fig. 5.

This satellite was of the size of a bus and was brought into a Low Earth Orbit in an altitude of 476 km in 1984 (Murr & Kinard, 1993). It contained more than 10,000 test material plates which were exposed to the rather unfriendly environment of the LEO for degradation studies. These surfaces were exposed to bombardment by micrometeorites and near-earth space debris of man-made origin which led to a deterioration of the plates' surfaces. The LDEF day was only 90 min long as well as its night. With this frequency, the temperature varied from +100°C to -100°C! In addition during sunshine a most intensive UV-radiation was also hitting the surface. This effect combined with atomic oxygen (Atox) which is also present due to the last traces of the earth's atmosphere in this altitude. The combined action of these influences resulted in interesting corrosion and erosion phenomena (Murr &

Fig. 5. View of the LDEF-experiment exposed in LEO (Courtesy of NASA Langley Research Center)

Kinard, 1993). The satellite was not retrieved after the planned exposure time due to the Challenger disaster. Only in 1990 after 34,000 earth orbits in 2105 days the LDEF-experiment was retrieved in the last possible moment by the Space Shuttle, fig. 6. It was taken into the shuttle in an altitude of only 333 km shortly before the satellite would have burned down in the upper atmosphere.

However, due to its very long exposure time, corrosion and erosion phenomena were very pronounced and a lot of interesting and alarming observations were made (Mandeville, 1991). One of the most alarming finds was that more than 80% of all investigated particle impact craters by SIMS turned out to be caused by terrestrial (man-made) and not by cosmic particles. The highest percentage of these particles was Al_2O_3-particles stemming from solid state rocket fuels. This was the reason why Russia finally changed over to liquid fuel systems. However, not only Al_2O_3-particles of terrestrial origin had been detected. Titanium- and cadmium-rich particles were also registered. They originated from paints with which rocket surfaces had been painted. Particles of stainless steel, mineral particles and such of silver-solder had also been detected (Murr α Kinard, 1993). The geometry of the impact craters of particles allowed calculations of the velocity of impacting particles. SIMS-results on the composition of extraterrestrial particles yielded another interesting detail: Many analyzed cosmic particles exhibited nearly the same composition as so called chondritic (C1) meteorites (main constituents: Si, Al, Mg, Fe, Ca, O) (Stadermann, 1990). It is believed that the solar nebula from which our solar system developed 4.5 billion years ago had the same chondritic composition. Eventually the planets and other bodies developed, the composition of which varies considerably and deviates from this original composition because of diverse chemical processes (so called fractionations). However, material with chondritic composition is still found in some meteorites and many cosmic dust particles. This is an indication that these objects are of "primitive" nature, i. e. very old and unchanged material (Stadermann, 1992).

Fig. 6. Recovery of the LDEF-experiment from LEO.

6. Rocket and other space debris: mortal danger in near Earth space

It must be mentioned that surface erosion by cosmic dust is not the only danger of material degradation in space. Especially near the earth, there is eminent danger of collision with much greater "particles" of space debris. The reason is a rising number of debris items with more than 10 cm diameter, mainly rocket parts and abandoned satellites which all circle around the earth with about 36 000 km/h. Another 100 000 parts with diameters between 1 and 10 centimeters and another billion of parts with diameters below 1 cm complete this symphony of danger for space vehicles near the earth (Spiegel, 1995). Among the very small parts are also minispheres of human debris which were ejected from space vehicles. It goes without saying that a collision with such parts can cause heavy damage of a satellite or a space vehicle. In November 1995 the US space Shuttle "Columbia" was hit by a small part – presumably an electronic structural part. After return to earth an impact crater of six millimeters in depth and two centimeters in diameter was detected in the hatchway of the shuttle. If this part would have hit the oxygen tank of the shuttle an explosion would have been inevitable. Since it is to be expected that the number of such parts will rise in near earth space it could be that in a couple of years a safe travel of space vehicles in this region will not be possible any more (Spiegel, 1995, Schmundt, 2003). This would cause a throwback of mankind into a technological "stone age". If used up satellites can no longer be replaced, satellite television, GPS, wireless global phone calls, and many other services of today will cease to operate. Hence LEO has become something like an international waste disposal. Well over 150 000 scrap parts of earlier space missions race around the earth: Old and inoperable satellites, rocket parts, diverse metal parts, astronauts gloves, metal tools etc. (Schmundt, 2003). They have become the primary danger for space flights in LEO. No

wonder that the NASA has installed a watch center which has registered larger pieces of space-scrap in something like a space-emergency map in order to save space shuttles and rockets from collisions with scrap (Schmundt, 2003). The European Space Operations Centre (ESOC) in Darmstadt (Germany) has also installed a Space Debris-working group with the same responsibility. Furthermore, a series of Space Debris Conferences has been installed by the European Space Agency (ESA) which took and take place in Darmstadt (Germany). The Fifth European Conference on Space Debris just took place from March 30 to April 02, 2009 at the ESA Space Operations Center (ESOC) in Darmstadt (Congrex 2009). It was the largest dedicated event on space debris issues. It was co-sponsored by the British, French, German and Italian space agencies, the committee on Space Research and the International Academy of Astronautics.

Most astonishingly there exists no regulation which would forbid the generation of space scrap in spite of the fact that an international Office for Outer Space Affairs (OOSA) is established in Vienna (Austria). Nevertheless, the prevention of generation of space scrap seems to be the most meaningful and urgent requirement for the prevention of a breakdown of space flight. There are several proposals of how to clean LEO from scrap but none of them has materialized due to financial problems. Without massive political pressure in all nations active in space flight a cleaning campaign in LEO is a hopeless case (Schmundt, 2003). The LEO is to a limited extent 'self-cleaning' because all debris will eventually enter the atmosphere and burn up, but the time scale of this process is highly altitude-dependent and will take tens to hundreds of years, even if no additional space debris was produced any more.

7. Degradation of solar cell samples

Solar cell arrangements and thermal MLI-blankets represent typical surfaces of satellite bodies. Hypervelocity impacts of microscopic projectiles can perforate these materials and may ultimately lead to system performance degradation. In order to quantify the particle impact history of samples returned from space it is necessary to know the relationship between impact parameters and resulting crater morphology. For this purpose particles were shot at solar cells and thermal MLI-blankets under controlled conditions at the Ernst-Mach-Institute as part of the ESA/ESTEC project (Schäfer & Schneider, 1994). The objective in that collaboration was to determine to which extent it is possible to deduce impact parameters such as angle, velocity, projectile mass and, possibly, composition from the study of those impact craters. The analytical methods we used included optical and scanning electron microscopy, electron microprobe, and – to a limited extent – secondary ion mass spectrometry (Stadermann et al., 1997; Heiss & Stadermann, 1997). The investigations demonstrated that it is possible to determine some of the parameters of a hypervelocity impact onto solar cell arrangements and thermal Multi-Layer-Insulation blankets by studying crater characteristics like its dimensions or inclination. For several relationships, correlation curves have been found which can be used for calibration. Thus, it is possible to determine important characteristics of the particle environment in space by the study of impact features on satellite components retrieved from low earth orbit. The chemical composition of particle residues can only partly be determined on the retrieved satellite components that consist of complex materials. Essentially, an identification of projectile residues is only possible if the elemental contents of projectile and target are very different.

Fig. 7. shows the famous Hubble Space Telescope (HST) during the first servicing mission in December 1993 after the installation of the solar panels.

It should be mentioned that astronauts gave the HST a probably last overhaul in May 2009 (Carroll, 2010). It will give Hubble several more years of life riding high above Earth's atmosphere haze. "The best times for this telescope are ahead of it" says Hubble Project Scientist Ken Sembach of the Space Telescope Science Institute. With the telescope's now greater imaging sensitivity and resolution, its new images will be spectacular.

8. Conclusion

The probably most interesting conclusion of this survey is the rarely so obvious observation how closely related an initially purely basic research can be to applied materials research.
What started out as a study of the elemental properties of cosmic dust evolved into an investigation of the degradation of space exposed surfaces and the safe differentiation between cosmic and terrestrial particles on materials surfaces. Thus the considerable danger of a certain rocket fuel technology for the life time of satellites in LEO could clearly be demonstrated.

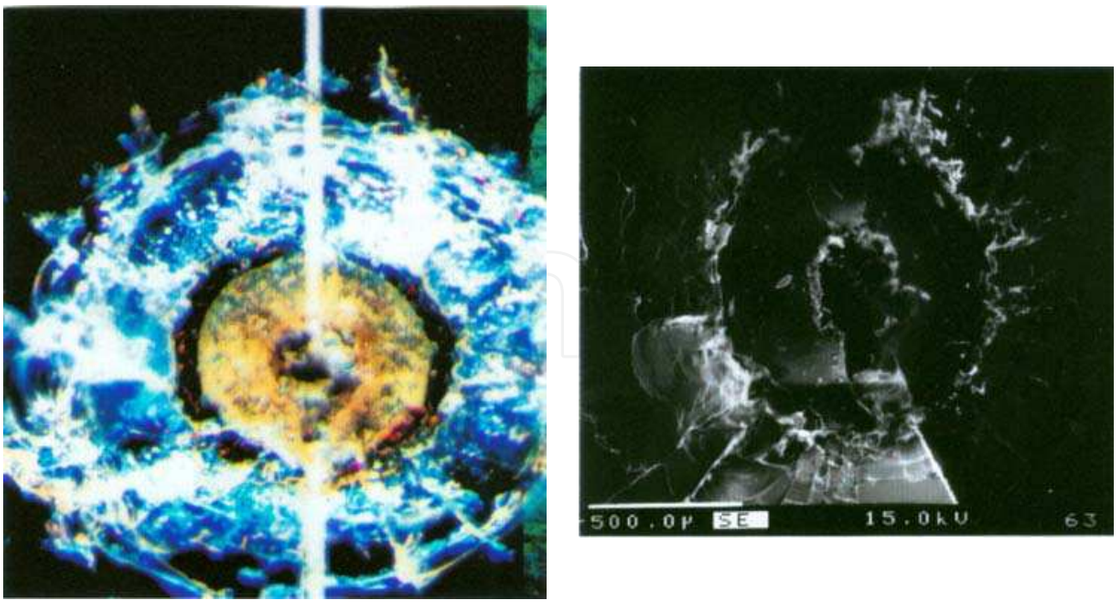


Fig. 8. shows a photo and a secondary electron image (of a scanning electron microscope) of a particle impact on a solar cell sample of the Hubble Space Telescope (Heiss & Stadermann, 1997)

This consequently caused the elimination of this technology in spite of previous great political tensions caused by this discussion. A further respective consequence was the introduction of small protective shields in flight direction especially for satellites in LEO which should operate for a long time. Basic research has thus definitely influenced applied space technology. The positioning of satellites in LEO for long duration is of great importance not only for military reconnaissance but also for modern communication and positioning systems, for global catastrophe survey and many other geopolitical surveys. Without the availability of proper topochemical and analytical technology a respective life time evaluation would not have been feasible. It seems also worth mentioning that SIMS is the key topochemical method for these investigations. The need to analyze particles in the single micrometer range triggered the development of a new SIMS-instrument generation with a much advanced lateral resolution in the upper nanometer range – the NanoSIMS 50 of CAMECA (Schuhmacher et al., 1999). Respective mass spectrometric results are not presented here in order not to unduly lengthen this article. The most important results are given in (Stadermann, 1990 and 1992).

The Hubble Space Telescope is powered by solar cells which are mounted on two flexible solar array wings. These solar array wings have been replaced after almost four years in space. One of these solar array wings was brought back to earth, while the other one was jettisoned. The retrieving of this solar array was a unique possibility for the investigation of the conditions in the low earth orbit. This wing was exposed to a permanent flux of micro particles. Since it was of interest whether these particles were man-made debris or micro-meteoroides, the European Research and Technology Centre (ESTEC) decided to disassemble two of the ten solar panel assemblies for further investigation in which our group participated.

It is not surprising that the investigation of Interplanetary Dust has developed to a most important scientific discipline in the Space Sciences. Dust is an essential component throughout space. It constitutes a considerable part of the total matter of our universe (Brownlee, 1978, Grün et al., 2001). Consequently, material degradation by micrometeorites is one of the common phenomena space flights have to cope with. It is also a fascinating result of this young scientific discipline that a part of the particles which come into the vicinity of our earth will eventually be trapped by the earth's gravity pull. Hence, our planet is collecting cosmic dust daily in a quantity of several tons. This leads to the conclusion that cosmic dust is not as exotic a material as we usually think. And every time we dust our window sills or book shelves we can be sure to clean particles from Deep Space, too.

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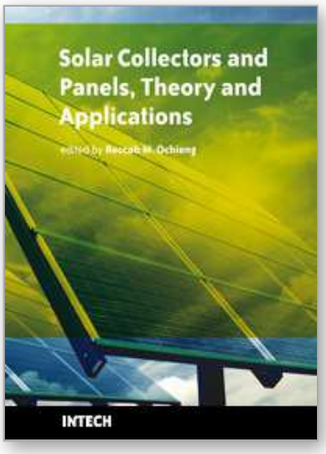

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