In-situ Observations of Space Debris at ESA

Gerhard Drolshagen
ESA/ESTEC/TEC-EES, Keplerlaan 1, NL-2201 AZ Noordwijk
e-mail: Gerhard.Drolshagen@esa.int

ABSTRACT

Information on the small size (millimetre or smaller) space debris and meteoroid population in space can only be obtained by in-situ detectors or the analysis of retrieved hardware. Every spacecraft in orbit will encounter those particles with certainty. The European Space Agency has an active programme in this field. Past, ongoing and planned ESA activities are presented. The in-situ observations cover the particle size range from sub-micron to millimetres. Overviews are given of the GORID detector in GEO and the DEBIE detectors in LEO. Summary results from the impact analysis of the retrieved solar arrays of the HST telescope are presented. Finally, evidence for impacts on the CCDs of the XMM-Newton telescope is given.

1. INTRODUCTION

GORID (Geostationary ORbit Impact Detector) was ESA's first impact detector aimed specifically to measure the population of small size space debris. It was operating in GEO from 1996 until 2002. This impact ionisation detector had a sensor surface of 0.1 m^2. Until July 2002 when the spacecraft was shut down it recorded more than 3000 impacts in the micrometre size range. Inter alia, GORID measured numerous clusters of events, believed to result from debris clouds, and indicated that debris fluxes in GEO are larger than predicted by present models [1-3].

Another in-situ detector, DEBIE-1 (DEBris In orbit Evaluator), was launched in October 2001 and is operating on-board the small technology satellite PROBA in a low polar orbit. It has two sensors, each of 0.01m^2 size, pointing in different directions [4]. A second detector of this type, DEBIE-2 with 3 sensors, is ready for flight on the EuTEF (European Technology Exposure Facility) carrier which is an external payload to ISS. The data from GORID and DEBIE-1 are analyzed and stored on-line in EDID (European Detector Impact Database [2,3,5]).

Post-flight impact analyses of retrieved hardware provide detailed information on the encountered meteoroid and debris fluxes over a larger range of sizes than is possible with active impact detectors. ESA initiated several analyses in the past ((EURECA, Hubble Space Telescope (HST) solar arrays) [6-10] . The most recent impact analysis was performed for the HST solar arrays retrieved in March 2002 [7-9]. Measured crater sizes in solar cells ranged from about 1 micron to 7 mm. A total of 175 complete penetrations of the 0.7 mm thick arrays were observed. A chemical analysis of impact residues allowed the distinction between space debris and natural meteoroids. Space debris was found to dominate for particle sizes smaller than 10 microns. For particle diameters between 10 microns and about 1 mm impacts are mainly from meteoroids [7,9,10].

The paper concludes by presenting evidence for several unintended in-situ impacts which were encountered by the CCDs of the XMM-Newton x-ray telescope [11,12].
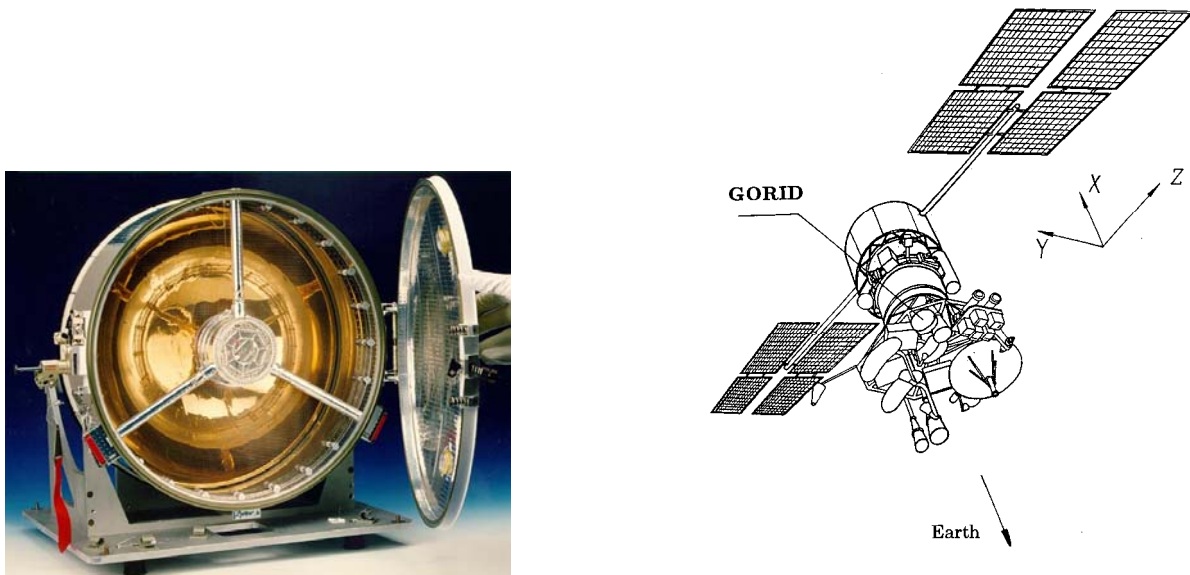
2. GORID DETECTOR IN GEO

GORID was launched into geostationary orbit in September 1996 as a piggyback instrument on the Russian Express-2 telecommunications spacecraft. The instrument began its normal operation in April 1997 and ended its mission in July 2002. It is the refurbished engineering model of the Ulysses dust detector, which detects particles by impact ionisation methods [1]. In this method of detection, a particle impacting the detector at hypervelocity speed creates a plasma of electrons and ions. The electrons and ions generated during the impact are measured separately.

The velocity and mass of the impacting particle are deduced from the rise-time and total intensity of the measured plasma signals using empirical calibration curves. The rise times of the measured plasma signals are independent of the particle mass, and decrease with increasing particle speed. Given the sensitivity and the calibration of the instrument, GORID can detect particles with a mass down to 10^{-17} kg.

The size of the instrument's hemispherical aperture is 0.1 m^2 , with a detector opening of 43 cm, and a viewing angle of 140 degrees. The GORID detector was in a geostationary location at 80 degrees East longitude until June 2000, when the satellite was moved to 103 degrees East.

Fig.1 shows the GORID detector itself and the geometry of GORID/Express in orbit (correct scale). The +Y-axis points towards the flight direction. GORID's main axis points 65° from the flight direction towards north and 5° towards Earth.
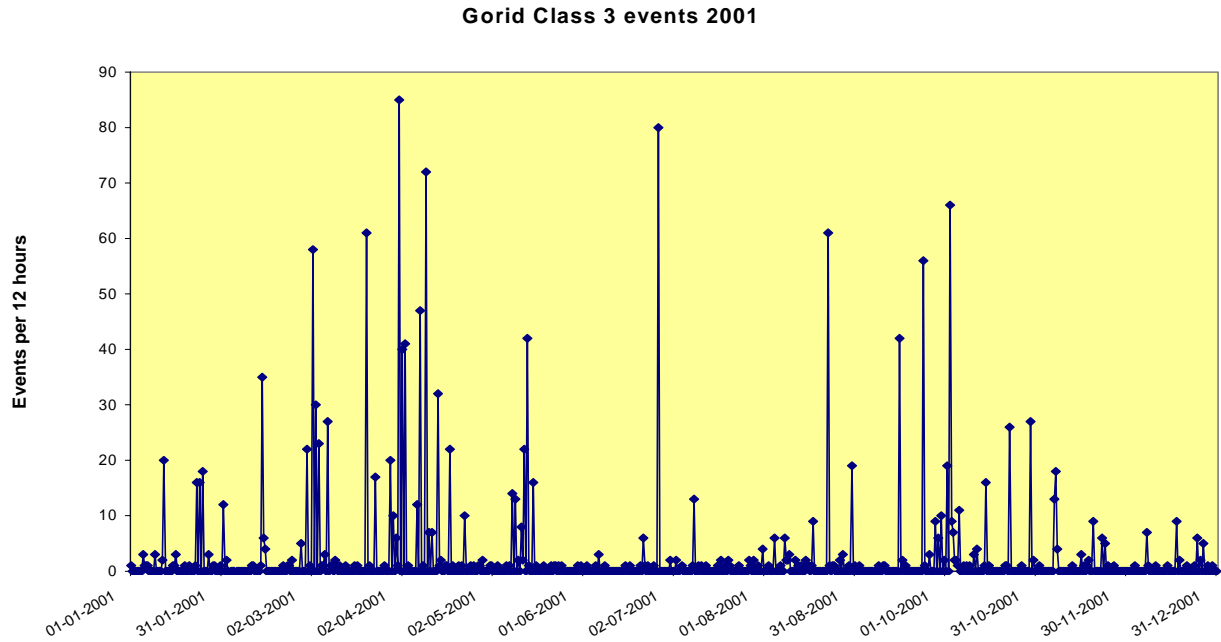

Fig. 1: The GORID impact detector and GORID/Express in orbit (correct scale). The +Y-axis points towards the flight direction.

Recorded events are calssified on-board into 4 classes with class 3 events being of the highest quality and are believed to be true impacts.
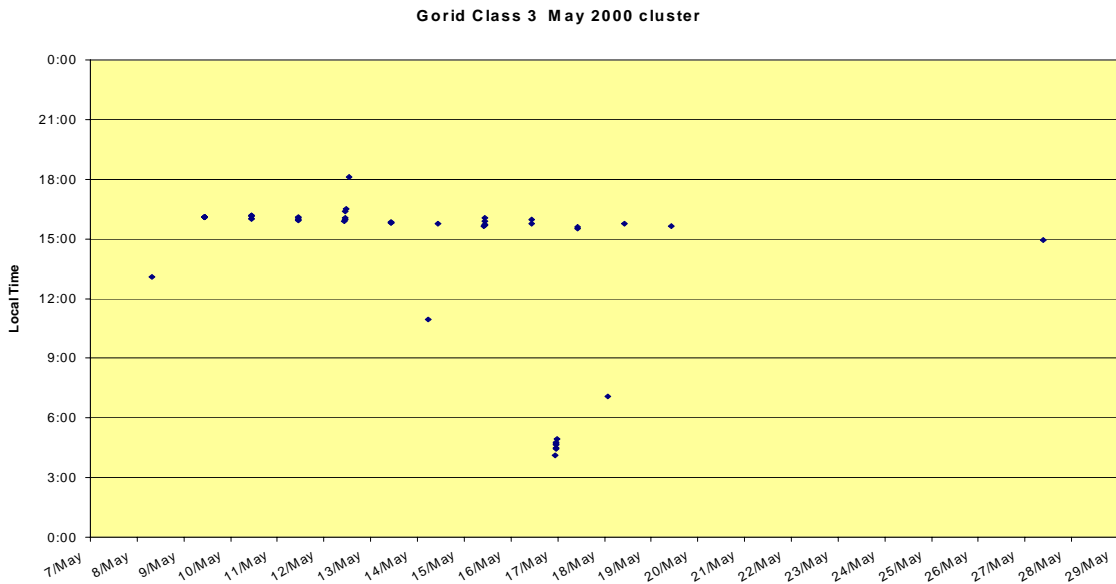
Fig. 2 shows the number of "class 3" events per 12 hours measured by GORID in 2001.

Very large variations in daily event rates led to the identification of clusters of events, some of which re-occurred on consecutive days at the same local time [1-3]. Fig. 3 shows an example of a cloud event detected in May 2000. During 11 days impacts were detected every day between 15:00 and 16:30 Local Time.

In GEO natural meteoroids and man-made debris should be distinguishable by their impact velocities. Even debris in highly eccentric orbits, like GTO, should impact with less than 5 km/s while meteoroids will typically be faster with the majority impacting with 10 -20 km/s. Unfortunately, the rise time measurements by GORID were found to be unreliable, likely as a result of interference from the energetic plasma in GEO. However, using time correlations it was still possible to separate meteoroids and debris statistically [2].
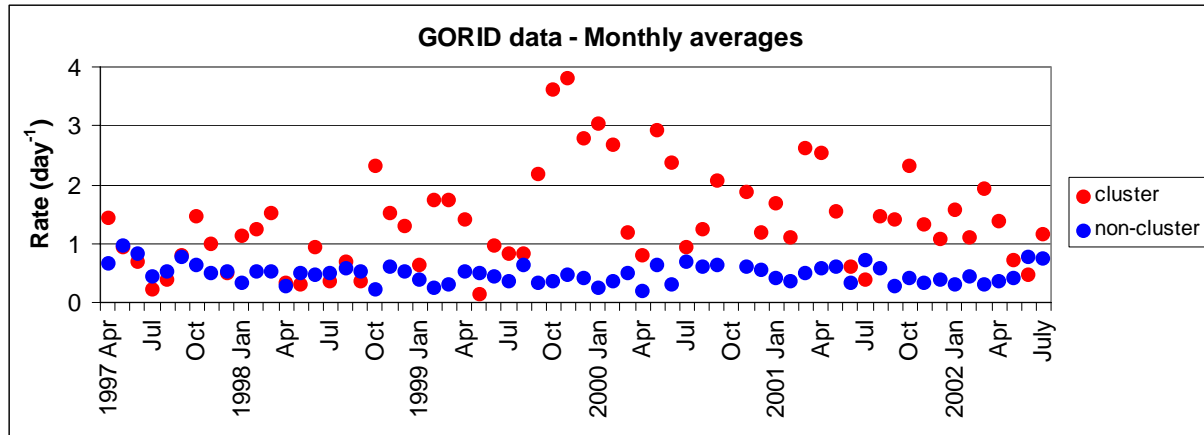
Gorid Class 3 events 2001

Fig. 2: Number of so called "class 3" events (which are supposed to be real impacts) per 12 hours measured by GORID in 2001.

Gorid Class 3 May 2000 cluster

Fig. 3: Example of a cloud event detected by GORID in May 2000. Every dot marks one recorded impact at the given day and local time. During 11 days cluster of events were detected every day between 15:00 and 16:30 Local Time.

Figure 4 shows the monthly average impact rate recorded by GORID throughout its mission. Events are either classified as cluster or non-cluster. An impact event is supposed to belong to a cluster of events, if the time span between two subsequent events is less than 0.05 days (corresponding to 1.2 hours). The detailed analysis of the data strongly indicates that cluster events result from debris while non-cluster events are mainly from natural meteoroids [2]. The total number of class 3 events was 3349 (2477 clustered, 872 non-clustered) in 1827 days.

Fig.4: Monthly average impact rate recorded by GORID. Clusters have less than 0.05 day interval between subsequent events. Cluster events are largely impacts from debris, non-cluster events from meteoroids.

The detection rate of meteoroid events was 0.54 d^{-1} and of debris events was 2.46 d^{-1}.
The mean fluxes were 1.35 x 10^{-4} m^{-2} s^{-1} for meteoroids and 6.1 x 10^{-4} m^{-2} s^{-1} for debris.

Some of the debris clusters were interpreted as clouds of aluminium oxide debris resulting from the firing of solid rocket motors. But there is evidence for the existence of currently unknown cloud generation mechanisms in GEO [2,3]. Additional impact detectors on GEO could improve the knowledge about the GEO particulate environment significantly.

3. DEBIE DETECTOR IN LEO

The DEBIE instrument [4] is based on a prototype sensor unit developed at the University of Kent at Canterbury (UK). The idea is to combine several different detectors to improve the reliability of the measurement. Patria (FIN) has been the prime contractor for the DEBIE development.

The DEBIE instrument consists of a Data Processing Unit (DPU) and up to four Sensor Units (SU). The Sensor Units can be placed on different sides of the spacecraft to detect particle impacts from different directions. The data from each particle impact is classified and logged by the DPU for further telemetry transmission to the ground station via the spacecraft's on-board data handling.

Each Sensor Unit implements a basic impact detector measuring the plasma generated by the impacts, the momentum and penetration of a thin aluminium foil. The detecting area of each Sensor Unit is 10 x 10 cm. Two plasma detectors are placed in front of a thin aluminium foil. They measure the plasma (one for electrons and one for ions) generated by the particle impacts on the foil. Two piezoelectric transducers are coupled mechanically to the foil and measure the momentum of the impact. Particles, with sufficient energy to penetrate the foil, are detected by the plasma detector (electrons) placed behind the foil. The particle velocity and mass can be calculated from the measured parameters with the aid of predefined calibration data. The instrument can detect particles with a mass of 10^{-17} kg or larger (depending on the impact velocity).
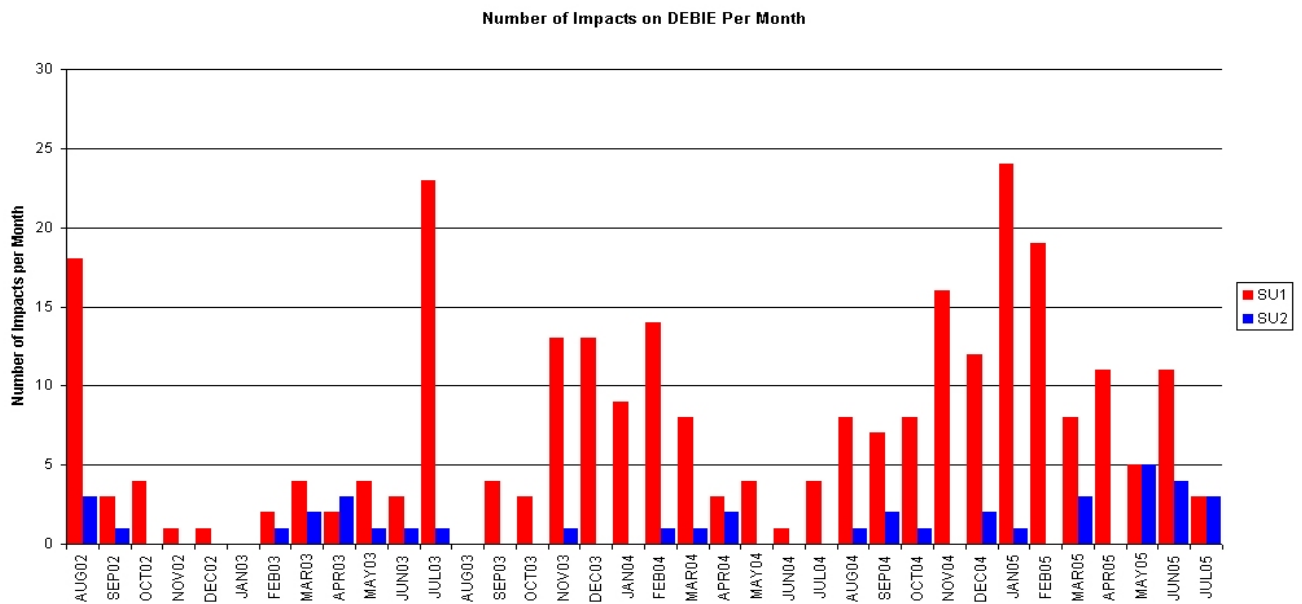
The coincidence measurement in different channels provides detailed information on impact parameters and allows to better distinguish between real impacts and noise events.

DEBIE-1 was launched to a low polar orbit on-board the PROBA satellite on 22.10. 2001 using an Indian PSLV launcher from Shriharikota. The satellite integrated already on the launcher is shown in Fig. 5 with one of the DEBIE Sensor Units visible in the lower right corner of the satellite. Following a commissioning phase DEBIE-1 is in normal operation since August 2002.

Fig. 5: Left: the DEBIE-1 flight model with 2 sensors units. Each SU area is 10 cm x 10 cm. Right: One SU of DEBIE-1 is visible at the bottom right corner of the PROBA satellite.
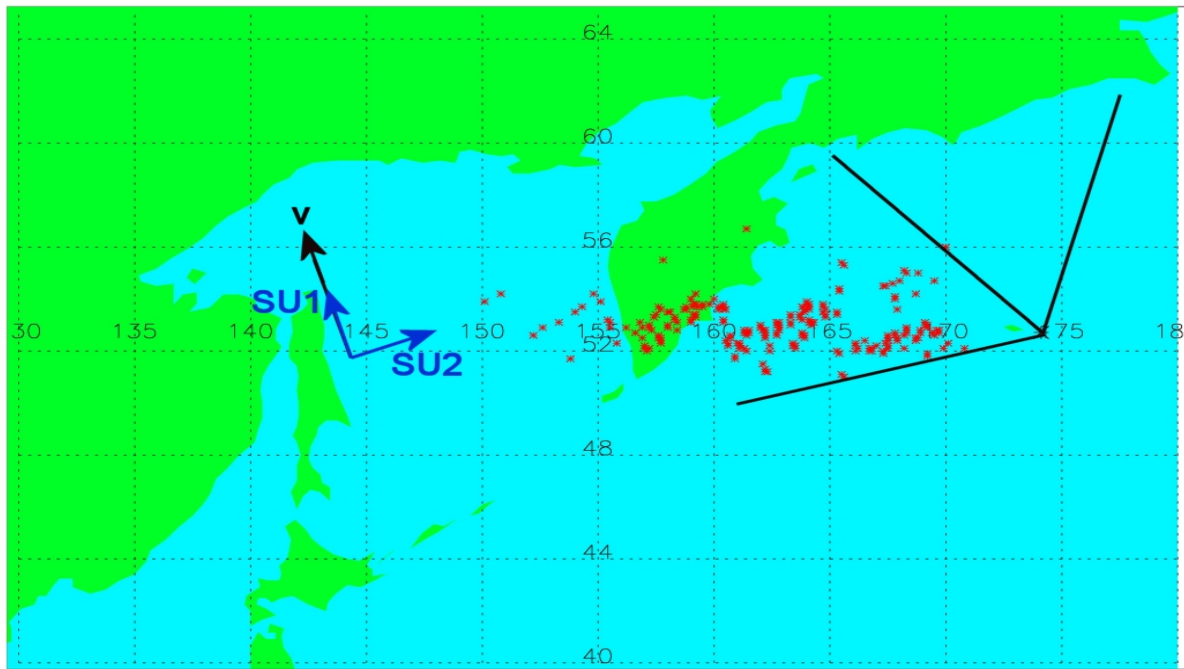
Figure 6 shows the monthly averaged number of impact events recorded by DEBIE-1. When converting these numbers to fluxes the on-times of DEBIE-1 have to be considered. These improved from as low as 33% in August 2002 to typical values between 60% and 90% in later months. Comparison of fluxes derived from DEBIE-1 measurements are in broad agreement with the latest meteoroid and debris flux models [2].

Fig. 6: Number of impacts on DEBIE-1 per month from August 2002 – July 2005. SU1 (red bars) is facing in-flight, SU2 (blue) to the starboard direction.

When analysing the DEBIE-1 data it became soon obvious that this highly sensitive detector was susceptible to noise from several different sources, like ambient plasma, fields and ground currents on PROBA, structural noise from temperature changes and changing sun-light illumination. This required the development of filtering methods which in the end allowed a convincing separation of real impacts from noise events. This was only possible because DEBIE-1 records different signals and delay times which can be used for coincidence analyses [2,5]

One specific type of noise was identified as signals from the Cobra Dane radar on Shemya island. False impact events were recorded by the SU 2 when it passed through the cone of the operating radar. The location of DEBIE/PROBA when these events occurred is shown in Fig. 7 [2,5].

Fig: 7 False events triggered in Sensor Unit 2 of DEBIE-1 by the Cobra Dane radar on Shemya Island

A second flight unit, DEBIE-2 with 3 sensors is scheduled to be flown at the International Space Station as part of the EuTEF external payload.
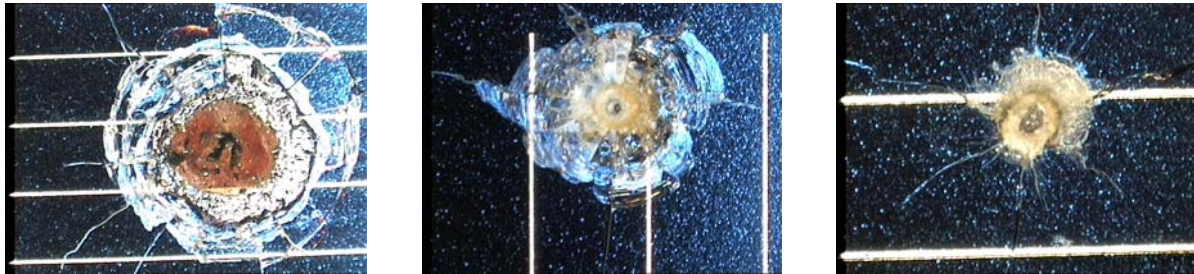
4. POST-FLIGHT IMPACT STUDY OF HST SOLAR ARRAYS

Studies of retrieved space hardware provide unique information on the meteoroid and debris populations in space. The impact flux information, which can be obtained from exposed surfaces, increases with surface area and exposure time. Returned flight hardware can have much larger exposed surfaces than dedicated in-situ detectors. This offers the opportunity to sample the flux of larger particles, up to millimetre sizes [6].
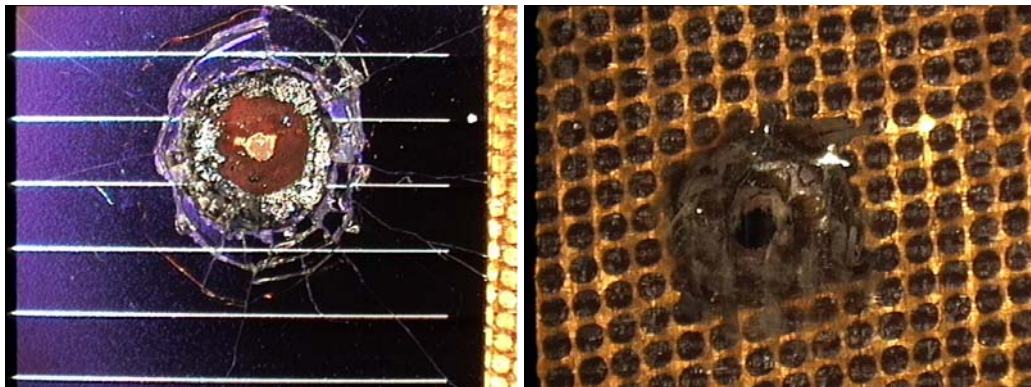
Two complete HST solar array wings were retrieved in March 2002 by the Shuttle Columbia. These HST solar arrays had been deployed during the first servicing mission in December 1993. The total exposure duration from deployment until retrieval was 3011 days (8.24 years). The HST orbit was nearly circular around 600 km altitude at an inclination of 28.5°. With a total exposed area of 120 m^2, of which about 40 m^2 are covered by solar cells, the arrays provide the largest survey area of a single substrate ever retrieved and present a unique opportunity to gain information on the meteoroid and space debris population in space. The HST solar arrays are thin and flexible. The total thickness of the arrays (cover glass, solar cell and backing structure combined) is only about 700 microns.

A post-flight impact investigation was initiated to record and analyze the impact fluxes and any potential resulting damage [7-9]. The study began with a global survey of large impact features on all exposed surfaces. This was followed by a detailed survey of smaller impacts on selected surfaces in several laboratories. For each size regime sufficient craters were recorded and analysed in detail for statistically meaningful results. A database with pictures and impact feature parameters and measurements was created.

Typical examples of impact features on the HST solar array are shown in Figs. 8 and 9.The white stripes of the electrodes are spaced by 1.25 mm providing a convenient size measure.
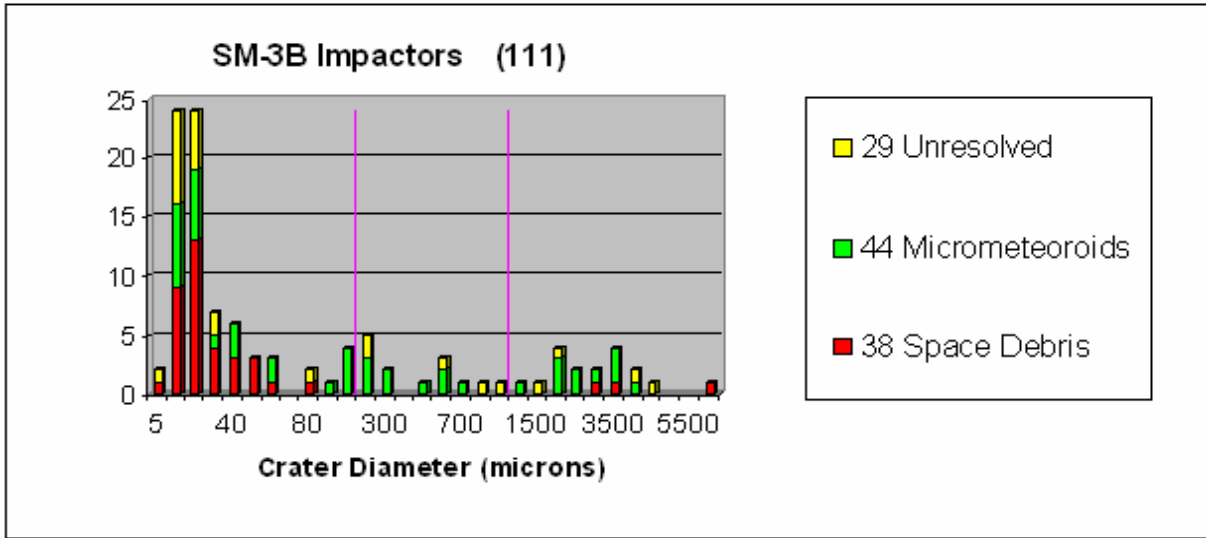

Fig. 8: Impact craters on HST solar cells. Crater diameters from left to right are 4 mm, 2 mm and 0.6 mm.

Fig. 9: Front and rear side of impact feature on HST solar array. The crater is 5 mm the central hole 0.5 mm in diameter.
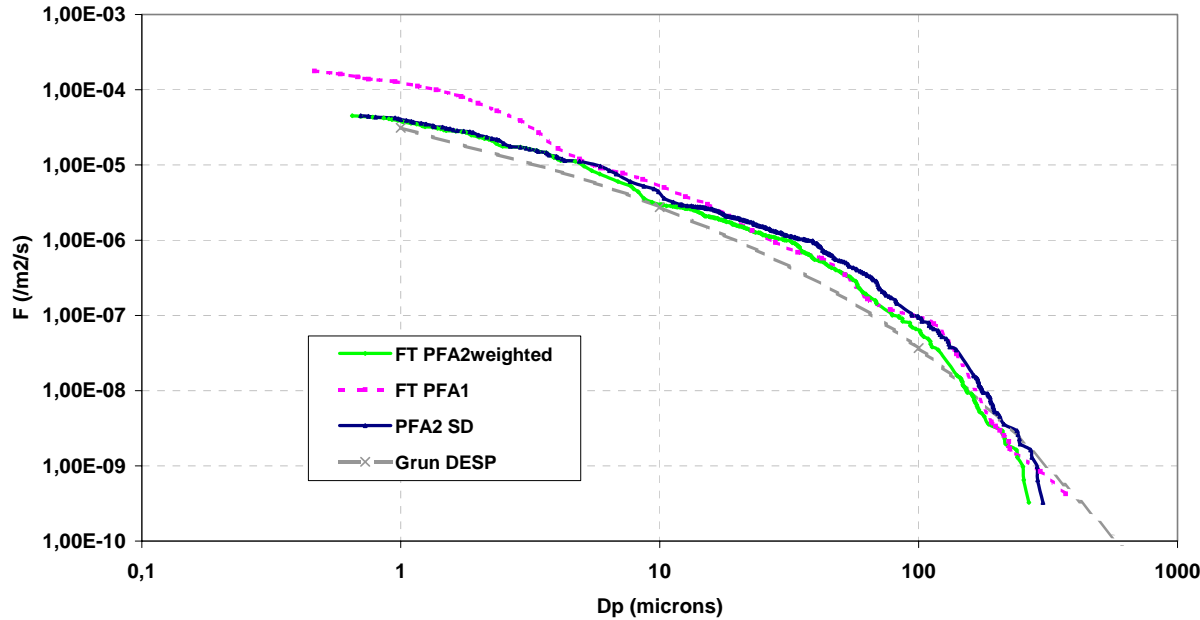
Fluxes were derived from the number of craters counted and measured within the known survey area, and these data were compared with current numerical flux models and the results of the first survey performed on the HST wing retrieved in 1993. For the comparison with flux models a conversion from crater size to particle size has to be performed. This was done with the help of an experimentally derived calibration curve which had already been developed during the HST post-flight studies after the retrieval of one array in 1993 [6].

Chemical analysis by electron beam studies has been performed at two laboratories to determine the nature and origin of the impactors [9,10]. A suite of large craters and randomly chosen solar cell samples were used for chemical analysis of impact crater residues in order to distinguish meteoroids and space debris. Improvements in techniques have led to higher success at the discrimination between space debris and meteoroids as potential candidates. For very small craters, space debris is dominant, comprising largely aluminium oxide from solid propellant apogee boost motors but, significantly, the flux data differs from previous HST solar array cell studies. For medium size ranges, meteoroids clearly dominate but space debris is still a significant factor. Results of the chemical residue analysis for 111 craters are presented in Fig. 10

Fig. 10: Relative populations of meteoroids and space debris as obtained by analysis of chemical residues in impact craters of the HST solar arrays. Note scale breaks (purple lines) at 100 microns and 1000 microns.

The final consolidated flux curves for impacts on the HST solar arrays are shown in Fig. 11 (from [7]). Shown are cumulative fluxes as function of the particle size for the first (PFA1, array retrieved in 1993) and second (PFA2, arrays retrieved in 2002) HST analyses. The measurements are compared with the predictions of a reference meteoroid model (Grun DESP) [13]. For PFA2 two curves are given. They differ in assumptions made for converting crater to particle sizes. The curve PFA2 SD assumes that all impacts were caused by particles with typical velocities and densities of space debris particles, while the curve denoted 'FT PFA2 weighted' assumes relative abundances of meteoroids and space debris as determined by the chemical residue analysis.

Fig. 11: Cummulative impact fluxes (fluxes for given size or larger) as function of the particle size. The results for the HST solar arrays retrieved in 2002 (PFA2) are compared to those for the previous analysis of one array retrieved in 1993 (PFA1) and to predictions from the meteoroid reference model by Grün et al. [13].
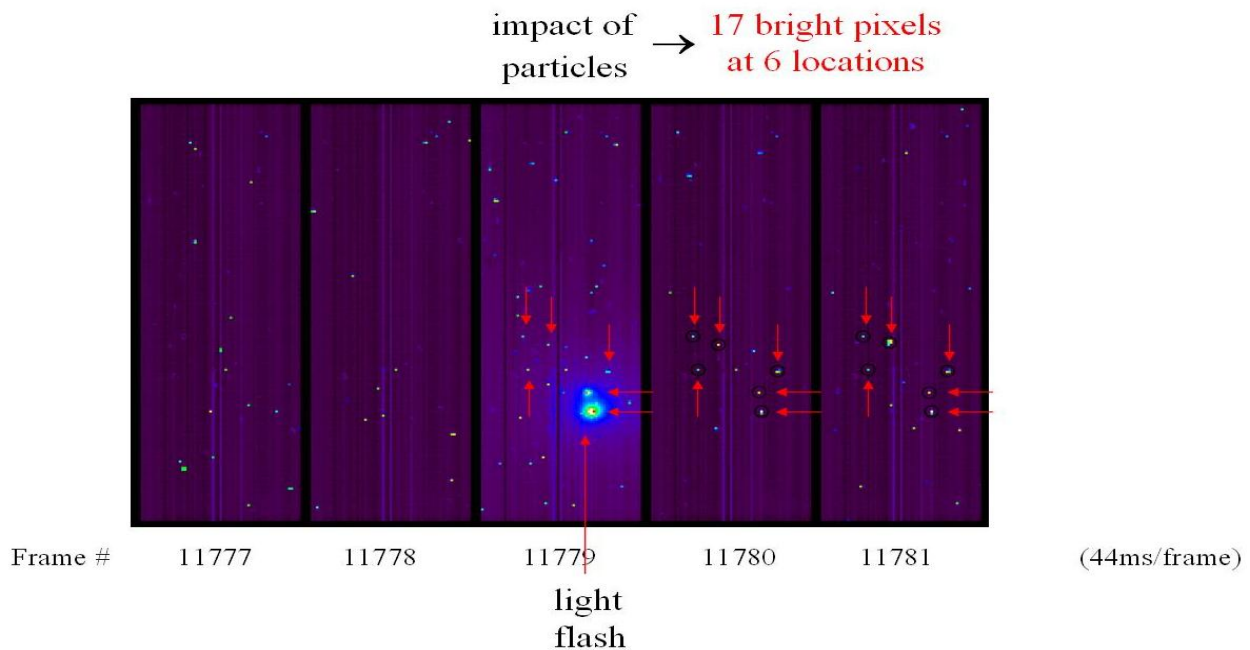
5. IMPACTS ON CCDS OF XMM-NEWTON

In-situ detection of impacting particles can also happen unintentionally. One example is XMM-Newton. The XMM-Newton X-ray astronomy observatory is operating since December 1999 in a highly eccentric 7000 km by 110000 km orbit with an initial inclination of 40°. Its parabolic mirrors system is made of 58 concentric Nickel alloys elements coated with 0.2 micron of gold. It is designed to image X-rays by grazing incidence reflection onto a focal plane, equipped with Charge Coupled Devices (CCDs). Particles, and in particular protons (but also micro meteoroids and debris), can reach the unshielded open section of the CCD detectors via transmission through the X-ray telescope, if the energy and the incidence angle are adequate. On 15 October 2000, at 115,000 km distance from the Earth, a sudden increase of the event count rate was observed simultaneously (within the resolution of the instrument of about 50 ms) on 35 CCD pixels [11]. The amount of locally generated leakage current could not be explained by ionising radiation of single ions. The hypothesis was made that a micrometeoroid scattered under a small angle off the X-ray telescope mirror surface finally reached the focal plane detector and produced the damage [11].

Little information was available on the physical phenomena involved in hypervelocity impacts at very small incidence angles. In order to better investigate such hypothesis, several impact test shots were performed with the dust accelerator at the Max Planck Institut für Kernphysik (Heidelberg, Germany). Micron sized iron particles were fired onto mirror samples made of gold coated Zerodur glass representing the XMM configuration. A witness target plate was located behind the mirror. Impact velocities were around 5 km/s and impact angles varied between 1 and 5 degrees from the mirror surface plane. The results showed that after almost every shot one or a few particles from either the projectile or ejecta did find their way through the target assembly. In addition the projectile(s) left the mirror almost parallel to the mirror surface with an exit angle much smaller than the incidence angle.

The results of one of these shots on a working CCD of the XMM-Newton type are shown in Fig. 12. The impact of a micron sized particle creates a bright flash and leaves several pixels permanently damaged. This reproduces very closely the in-orbit observations.

Fig. 13: Impact on CCD of XMM-Newton telescope. Result of laboratory impact tests of micron sized particle under grazing incidence.

To better understand the physical phenomena involved in hypervelocity impacts at very small incidence angles numerical simulations of grazing impacts on the XMM mirrors were performed with the AUTODYN-3D hydrocode [12]. These studies have fully confirmed the in-orbit observations and the results of the test shots: at grazing incidence a hypervelocity particle can be scattered almost intact from smooth surfaces.

By mid 2006 at least 5 potential particle impacts have been encountered by several CCDs of the XMM-Newton telescope. One impact in March 2005 disabled permanently one complete section of a CCD.

6.   ACKNOWLEDGEMENT

7.   REFERENCES

1. Drolshagen, G. et al., 'Measurements of cosmic dust and micro-debris in GEO', Adv. Space Res., Vol. 28, No. 9, pp 1325-1333, 2001.

2. Bunte, K.D. et al., 'Processing, Analysis and Interpretation of Data from Impact Detectors', Final Report of ESA contr. 16272/02/NL/EC, 2006.

3. Bunte, K.G. and Drolshagen, G., ´Detection and simulation of debris cloud impacts', Proceed. of 4th European Space Debris Conf., ESOC, Darmstadt, 18-20 April 2005.

4. Kuitunen, J. et al, 'DEBIE – First standard in-situ debris monitoring instrument', Proc. 3rd European Conf. on Space Debris, ESOC, 19-21 March 2001, ESA SP-473 pp 185-190 (2001).

5. Schwanethal, J.P. et al. 'Analysis of impact data from the DEBIE (DEBris In-orbit Evaluator) sensor in polar low Earth orbit', Proceed. of 4th European Space Debris Conf., ESOC, Darmstadt, 18-20 April 2005.

6. McDonnell J.A.M. et al., 'Meteoroid and Debris Flux and Ejecta Models', Summary Report of ESA contract 11887/96/NL/JG, 1998.

7. McDonnell J.A.M. et al., 'Post-Flight Impact Analysis of HST Solar Arrays - 2002 Retrieval', Final Report of ESA Contract No. 16283/NL/LvH, 2005.

8. A. Moussi, A. et al., 'Hypervelocity Impacts on HST Solar arrays and the Debris and Meteoroids Population', Advances in Space Research, Vol. 35, Issue7, pp 1243-1253, 2005.

9. Kearsley, A.T. et al. 'Impacts on Hubble Space Telescope Solar Arrays: Discrimination between Natural and Man-made Particles', Advances in Space Research, Vol. 35, Issue7, pp 1254-1262, 2005.

10. Graham, G.A., et al. 'The chemistry of micrometeoroid and space debris remnants captured on the Hubble Space Telescope solar cells', *International Journal of Impact Engineering*, 26, pp 263-274, 2001.

11. Strüder, L. et al., 'Evidence for micrometeoroid damage in the pn-CCD camera system aboard XMM-Newton', *Astronomy & Astrophysics*, Vol. 375, nr. 1, August III, pp L5-L8, 2001.

12. Palmieri, D. et al., 'Numerical Simulation of Grazing Impacts from Micron Sized Particles on the XMM-Newton Mirrors', Intern. Journal of Impact Engineering, Vol. 29, pp 527-536 (2003).

13. Grün, E. et al., 'Collisional Balance of the Meteoritic Complex', Icarus, 62, pp 244-277., 1985.