ON THE EXISTENCE OF DEBRIS CLOUDS IN THE SPACE STATION ORBIT

- Final Results of the EuroMir '95 Impact Detector -

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ABSTRACT

A flight experiment was attached to the MIR Space Station as part of the ESA programme, EuroMir '95. The goal of the experiment was to develop a better understanding of the effects of the space environment on materials. In addition to the active enumeration of particle impacts and trajectory, it was the intent of this experiment that hypervelocity particles be captured and returned intact to Earth. Measurements were performed post-flight on returned material to determine the flux density, diameters, and subsequent effects on various optical, thermal control and structural materials. In addition, sensors actively measured the atomic oxygen flux, contamination deposition and effects during the mission.

1. INTRODUCTION

The space environment is becoming a major concern for many of the space systems presently considered, including that of the International Space Station. This concern is due to a combination of fundamental issues. Ultraviolet radiation (UV) is present at all orbits. UV heats surface materials at low levels and can alter the chemical structure of susceptible materials. Atomic oxygen (AO) is present in low earth orbit (LEO). AO atoms cause erosion of surfaces and oxidation of susceptible materials. The debris environment is a dynamic process in which fragmentation due to collisions create additional objects of different sizes. Impacts from space debris cause damage to structural materials, sensors, reflective or refractive optics, solar cells, etc.

Today, potential impacts of orbiting man-made debris on spacecraft, presents one of the most serious space environmental threats to space missions. In the future, as the population of debris grows with increasing space traffic, the likelihood of debris impacts on spacecraft may very well become a critical problem.

During the STS-44 mission, the Space Shuttle corrected its altitude by 26 km to evade a spent upper stage. The object, which was slightly outside of the given collision ellipsoid, was determined to be the Kosmos 851 rocket body. Kosmos 851 was launched on 27 August 1976 into an 81° inclination orbit. Data from experiment sensors during this near encounter, suggest that a cloud of micron-sized particles existed in the vicinity of the object. Data also suggests that the flux density was nearly two (2) orders of magnitude higher than background flux typically experienced (Ref. 1).

In addition to confirming the existence of debris clouds (Ref. 2), analysis of the Long Duration Exposure Facility (LDEF) impact residue chemistry has revealed that the trailing surface of the platform had been impacted by a significant amount of man-made debris. However for that to occur, the impacting dust grains must be in elliptical orbits. The preponderance of data also suggests that the orbits must have perigees lower than the orbit of LDEF and considerably higher apogees. Crater morphology suggests the particles must have diameters 10 micrometers or greater. Sources that are the most plausible are i) particles released during GTO Solid Rocket Motor (SRM) operations and ii) particles released in the Molniya orbits. At 63.4°, the Molniya orbits could account for the highly elliptical craters observed on the south-facing tray clamps.

During the STS-56 mission, the shuttle maintained an attitude for most of the mission where the minus Z direction of the shuttle was aligned parallel with the local vertical [(-ZLV direction); cargo bay always facing the earth]. At the same time, the starboard "wing" of the shuttle was pointed in the direction of flight [(+YVV direction); starboard wing into the velocity vector]. That arrangement exposed several shuttle orbiter windows to ram direction particles. Remarkably, the STS windows received ten (10) recorded hypervelocity impacts on windows facing the direction opposite to the flight direction (Ref. 3). It is of interest to note that several of the impacts were elliptical in shape. Even though the direction of the ellipticity has not been determined, the fact that there are elliptical craters suggest that oblique impacts in the thermal panes may provide a means to assess directionality of the impact.

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Due to the high inclination of this mission, i.e., i = 57°, the trailing surfaces of the shuttle windows were exposed to a flux of particles which may be associated with the Molniya orbits. The fact that STS-56 flew a -ZLV attitude throughout most of the mission makes the trailing surfaces of the windows not only accessible to the particles receding from the Earth, but also those particles approaching the Earth enroute to a southern hemisphere perigee. The fact that Molniya orbits are at a critical inclination and thus resist precession means that any debris associated with the i = 63.4° orbit will tend to remain in a stable orbit. The near matching of the STS-56 mission orbit inclination with that of the Molniya orbits may well have increased the collision probability for the trailing faces of the thermal panes.

Recent data from the European Retrievable Carrier (EuReCa) and the Hubble Space Telescope flights (Ref. 4) suggest that the current models are conservative for predicting the number of impacts (flux) a spacecraft will receive from small particles (i.e., less than 0.8 millimeter in diameter), while the models predict a flux nearly a factor of 10 less than that measured for particles above 1.0 millimeter. The data observed at the larger sizes is well above the predicted values. This suggests one of several things; 1) the population density of larger sized particles is greater than believed at these higher altitudes (and by inference, those immediately above them) and/or 2) the growth rate at the larger sizes is equivalent or greater than that for the smaller sized particles and/or 3) that impacts caused by the intersection of the payload with orbiting debris clouds skew the integrated flux to an artificially higher value.

Because of these basic concerns and our recent findings, the flight experiment was manifested on the MIR Space Station as part of European Space Agency (ESA) programme to develop a better understanding of the effects of the space environment on materials.

The ESA mission, EuroMir '95, is now complete having launched an ESA astronaut (Thomas Reiter) to Mir in September 1995, for an ESA record six months stay on Mir. Another record was broken on this mission for ESA. The first EVA by an ESA astronaut was undertaken, lasting approximately 6 hours.

As part of the EuroMir '95 suite of experiments, a set of payloads containing surfaces to monitor the LEO environment was installed on an external platform called the European Science Exposure Facility (ESEF).

The ESEF platform was attached to the Spektr module prior to launch to Mir. Once permanently docked with Mir, the Spektr module pointed in the -Y position which during gravity gradient attitude can be in the velocity vector. The ESEF platform points principally in the Nadir direction on Mir. (Mir flys in a circular orbit at an altitude between 350km and 450km at an inclination of 51.6°).

The platform was designed by the Institut d'Astrophysique Spatiale, Paris Universitie XI, Orsay, France and is based upon KMP1 which flew successfully on Salyut 7. The platform has seven positions of which six are available for experiment installation, with one taken up for the electronics unit for the platform.

Figure 1 shows the platform attached to the Spektr module. This photograph was taken from the Space Shuttle during the STS-71 mission. A mechanism unit and a cassette that contains the experimental surfaces can be attached to any or all of the six experiment positions. The cassettes were vacuum sealed prior to launch to Mir and were commanded to open by the platform control unit (stationed inside Mir) to expose the surfaces. The mechanism unit contained the drive units to open the cassettes.

During the EuroMir '95 mission, Thomas Reiter installed two cassettes with mechanism units, the platform electronics unit and another experimental box called Instrument Comrade Active (ICA) to the platform during his EVA (Ref. 5). He also operated the command unit inside the Mir to open the cassettes and start the experimental phase.

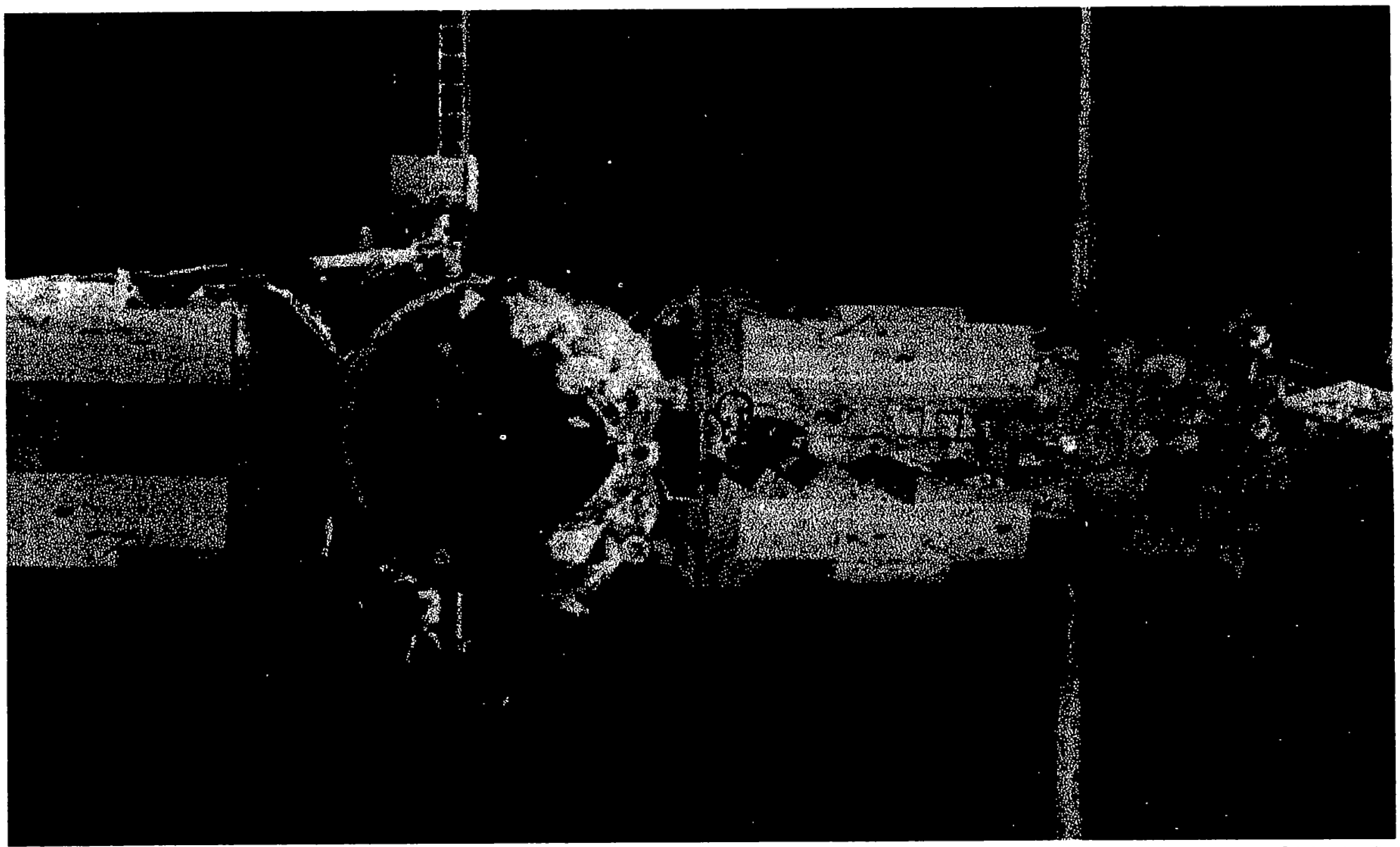
The command unit was used to close the cassettes. A second EVA was performed to retrieve the cassettes and return them to Earth for distribution to the relative Principal Investigators. The platform, electronics unit, and command units remain on Mir for possible further experiments at a later date.

2. SCIENTIFIC OBJECTIVES

The primary objective for this mission was: (i) to actively measure, in-situ, impacting particle parameters including trajectory, velocity vector, mass and flux distributions along with Atomic Oxygen flux and contamination mass deposition; (ii) identify the particle remnants of the micron-sized grains having impacted on purposely designed metallic collectors, for complete and detailed chemical, isotopic and organic analysis thereby determining grain composition, as well as the existence of organic and inorganic molecules; (iii) to return captured intact particles to Earth for complete and detailed chemical, isotopic, spectral, mineralogical and organic analysis thereby determining grain composition; (iv) to capture micron/submicron dust grains in a manner that insures minimal particle degradation.

2.1 ICA Environment Measurements

The principal detector for measurement of micrometeoroid and orbital debris fluxes and trajectories is the Momentum Stage (MOM) Impact Detector. The MOM impact detector, seen in Figure 2, are based on the use of the piezoelectric (PZT) impact detector (Ref. 6).



[photo courtesy of NASA]

Figure 1. ESEF Platform Attached to the Spektr Module of the Mir Station

MOM uses a very thin diaphragm to enhance sensitivity; it transmits via the bending wave, the normal component of the momentum exchange to PZT sensors mounted at the center of the impact plates. The ICA contains three impact plates, 100 cm^2, each. The instrument was built to perform measurements that result in the determination of the momentum (impact impulse) of the detected particle.

Longitudinal acoustic waves generated by impacts in the thin aluminium plate are detected by a single centrally-situated, Y-cut piezoelectric element composed of lead zirconate titanate (PZT) with a resonant frequency of 100kHz. This detector is capable of measuring momenta ranging from 6E-13 kg-m/s to 6E-08 kg-m/s.

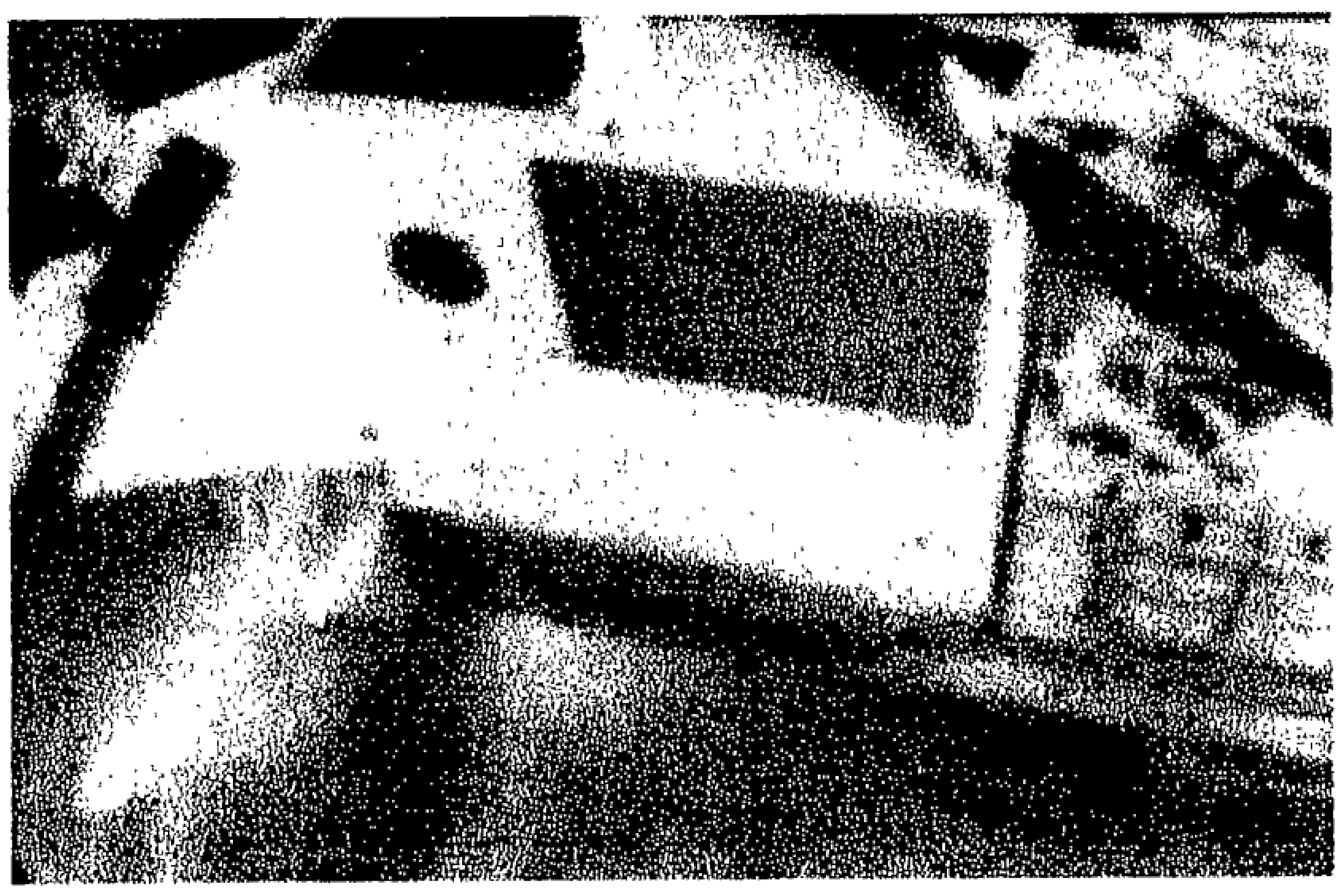


Figure 2. ICA Impact Detectors

The reliable determination of the trajectory of each individual dust or debris particle was a high priority of the proposed investigation. In addition to the particle trajectory, it was vital that dynamic particle parameters also be measured with a high degree of reliability. The basic parameters which the experiment measured and/or determined were the particles velocity and mass.

2.1 Intact Capture of HVI Particles

The return of extraterrestrial material to the laboratory was a primary goal of the ESEF experiment. The proposed investigation intends to retrieve relatively unshocked material by impacting three types of "underdense" capture devices. Shuttle experiments and the EuReCa mission have shown that both organic foam and aerogel materials can be successfully used to capture hypervelocity particles, intact. These capture devices were also complemented by the well-established technique of successive foils. Principal analyses and removal of captured particles are being performed at the Institut d'Astrophysique Spatiale, the University of Kent at Canterbury (UK) the Centre d'Etudes et de Recherches de Toulouse (France) and at T & M Engineering (USA).

3. ICA PRINCIPAL RESULTS

Active data from the MOM impact detectors reconfirm the existence of orbital debris clouds. This information is considered quite germane due to the similarity in orbital altitude and inclination of the Mir and International Space Stations. The data from this experiment suggest the existence of two reasonable size clouds of small size debris particles with momenta in the range of 4E-11 kg-m/s to 5E-10 kg-m/s. Fluxes average 8.96E-05 to 1.79E-04 impacts/s during quiescent periods. During intersection of the Mir station with the cloud, the flux varied. Maximum flux measured was 2.67 impacts/s. Figure 3 shows the ICA impact data for the period 24/10/95 to 16/01/96. Data were measured using the MOM3 detector. MOM3 was mounted on the side of ICA , and while not facing in the velocity vector direction, swept through the direction of flight once per orbit.

The periodicity is easily discernible during intersection of the first cloud. The sensors recorded a significant number of impacts approximately every 84 hours. Later, the impacts were observed approximately every eight to ten orbits.

The first cloud was observed for a period just over three weeks. After the first cloud no longer intersected the Mir station, all was quiet for nearly seven weeks and then the sensors indicated that the Mir station was intersecting a second cloud. Impacts observed on 20th November, 1995 appear to be connected with the Leonid meteor stream. The flux and momenta are consistent with published data. The structure of the clouds appear similar, although the first cloud measured provided two small "warning bursts". The first cloud was seen to precess to the west during the mission.

3.1 Finding the "Parent" Source

Determining the "parent" source of the clouds became a high priority in the data reduction. NASA/JSC was

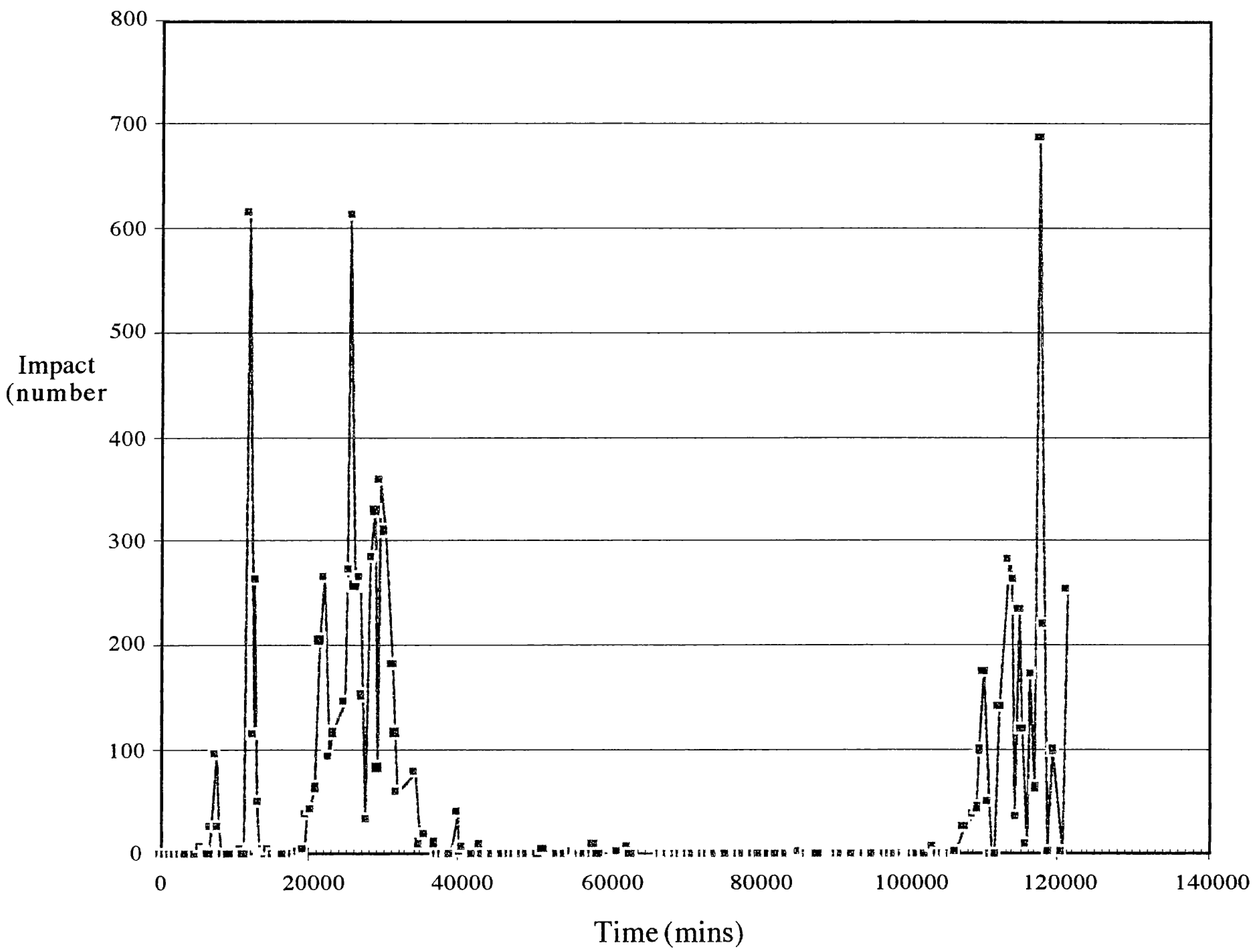


Figure 3. ICA impact data for the period 24/10/95 to 16/01/96. Periodicity of debris clouds measured using MOM3 detector.

contacted to support this investigation.

During the investigation NASA/JSC examined the data to find suggestive correlations for events at intervals of 84 hours (Ref. 7, 8).

After NASA/JSC retrieved the orbits (two-line element sets) of all spacecraft in the US Space Command Satellite Catalog with orbital periods similar to the cloud; only 11 objects were found in the catalog having periods greater than 80 hours. The principal subjects were Astron and its rocket body (R/B); Granat and its R/B; and Interbol 1, Magion 4, and their R/B's.

Using the Air Force Space Command validated program SATRAK, COMBO (Computation of Miss Between Orbits) was run for the Mir Space Station and the subject satellites listed above (Ref. 9). No firm correlations were found. Orbital plane intersections were also examined in case small particles had drifted around the orbit. Periods of high impact counts were selected. COMBO was run again for Mir and the entire satellite catalog (including tracked but uncataloged objects). All close approaches near these times appeared to be statistical in nature. No repeating satellites, and no apparent geometric conditions existed, e.g., passes occurring ahead or to the right of the Mir velocity vector. Re-examination of the data did not point to a source in a Molniya-class or GTO-class orbit, which might have been the source of large numbers of small particles, particularly from solid rocket motor firings.

Special analyses were conducted for known debris in the Mir vicinity, including those generated during EVAs. Again, no correlation was found.

Analysis will continue in search of other, less obvious potential particulate sources.

4. SUMMARY

Space-based systems exposed to the extreme environment of Low-Earth Orbit (LEO) will avoid catastrophic failures only if the materials which compose them can provide a "shield" against the effects of continuous hypervelocity impacts. Extensive research has been conducted to characterize the effects on materials subjected to hypervelocity impacts by large masses. Even though the large mass impactors carry the highest probability of precipitating a catastrophic event, the number of large mass objects which might be encountered by an exposed surface in LEO is believed to be quite small. However, the size distribution of objects a surface will encounter in LEO has not been adequately characterized; especially for that portion of the distribution which contains the largest number of objects, i.e., the smallest. In order to provide in-situ data depicting the size distribution of the most numerous objects in LEO, the ESEF/ICA was designed and flown aboard the MIR Space Station.

Two clouds of small particles were detected during a period of 100 days on the Mir space station. While no evidence could be found linking ICA major impact times with the catalog, the fact that large number densities of particles intersected the station should be of concern to ISS. The measured momenta of these particles suggest the size and velocity are such that they cause damage to optics and thermal control surfaces.

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