Japanese contribution to in-situ meteoroid and debris measurement in the near Earth space

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This paper reviews major results of present studies and recent developments for future missions in the Japanese space program regarding in-situ measurement and collection of micrometeoroids and orbital debris in the near Earth space. Japan's contribution in this area began with the post flight impact analysis of the Space Flyer Unit (SFU) satellite which was returned to Earth in 1996 after 10-month exposure in space. Despite a decade later than similar efforts first conducted in the USA and Europe, it resulted in a record of over 700 hypervelocity impact signatures, which now forms the nation's first database of real space impacts being open to public in the Internet. Together with laboratory impact tests, both morphological and elemental analyses of the impact craters yielded new insights of the meteoroid to debris ratio as well as flux variation compared with the previous spacecraft. The next step was a passive aerogel exposure in the STS-85 shuttle mission in 1997. No hypervelocity impact was found there but its experience has been incorporated for designing a microparticle collector to be on-board the Japan Experiment Module-Exposed Facility of the International Space Station. All of such "passive" collection of micro-impact features, however, still leave the significant uncertainty in the quest of their origins. Therefore an aerogel-based "hybrid" dust collector and detector (HD-CAD) is currently under the development. It measures time of impact and deduces impactors' orbital and physical parameters by detecting impact flash while still capturing them intact. The system is suitable for both (1) sample return missions in LEO as well as to parent bodies of meteoroids, i.e., comets and asteroids, and (2) one-way mission to where the thermal and plasma environment is such that impact induced plasma detectors may suffer from significant noise, e.g., a Mercury orbiter and a solar probe. Together with unambiguous dust samples from a comet by STARDUST and an asteroid by MUSES-C as references, the HD-CAD in the LEO will be able to deduce the accretion rates of the cometary and asteroidal dust grains on the Earth.

1. Introduction: A Brief History of the Micrometeoroid Research in Space

Despite its immensely significant contribution to the Solar System sciences, conventional meteorite research is always subject to luck of sample discoveries, unavoidable selection biases and chemical and physical alterations by interaction with the Earth environment. Micrometeorites collected from stratosphere, polar ice cores, and deep sea and in-land sediments also suffer from similar selection effects in terms of size, shape, magnetism, time resolution, etc., but to a lesser extent. If one wishes to eliminate all those obstacles in sampling unbiased extraterrestrial materials before interaction with the Earth environment (except its gravity enhancement and its spatial shielding of the meteoroid influx), in-situ measurement and collection of micrometeoroids in the near Earth space is the alternative. It can tell us about influx of extraterrestrial materials to the Earth at the smallest size regime at the present epoch. Such fluxes are largely governed by current balances of their respective sources and sinks from their

parent bodies, e.g., comets, asteroids, Kuiper Belt Objects, ejecta from planets and satellites and interstellar particles. Recent major discoveries of planetary sciences are closely related to the cosmic dust studies, such as dust disks around extra-solar planetary systems, pre-solar grains embedded in carbonaceous chondrites, Kuiper-Belt Objects, circumsolar asteroidal dust ring, large structures of cometary dust trails, and interstellar dust particles penetrating to the inner region of the Solar System. Thus understanding of origins, evolution and current state of the microparticulate population has become indeed a fundamental prerequisite for that of the Solar System.

However, the history of space measurement of dust grains began with a more operational reason than the scientific motivation. It started at the dawn of the space age, right after the Sputnik launch some 40 years ago, in order to assess risks of spacecraft paused by hypervelocity impact consequences due to meteoroids (e.g., McDonnell, 1978). Also, as the human space activity expands, an increasing threat of orbital debris hazards has required us continuous, in-situ measurement of the microparticulate environment in the near-Earth space (e.g., National Research Council, 1995). Thus, both "active detectors" and "passive collectors" of microparticles in space have been employed for most of interplanetary probes and retrievable spacecraft in the Low Earth Orbit (LEO) in the past, for the benefits of both the Solar System sciences and

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Table 1. Prospects of currently funded/selected in-situ cosmic dust studies and minor body exploration missions in 1996–2012 (as of November, 1999). Keys = **Sample Returns**, Active/Passive Dust Experiments, and *Minor Body Visits*. For the acronyms, refer the Appendix A.

Year	Japanese Programs	Other Nations (e.g., NASA & ESA)
1996	●**SFU-Post Flight Analysis (∼2000)**	●Galileo arrives Jupiter: DDS; Detection of interstellar dust & Io/Ganymede dust swarms ●Ulysses orbits Sun in Halo: UDD; Detection of interstellar dust ●NEAR launch (∼2000): No ●Shuttle-Mir launch (∼1997): MEEP/ODC ●**AMM samples from US South Pole Station**
1997	●**JARE-37 (1995∼): AMM samples arrive Japan from Dome Fuji** ●**STS-85: MFD/ESEM Aerogel** ●JARE-39 (∼1999): 1st AMM expedition	●*NEAR Mathilde flyby* ●Cassini/Huygens launch (∼2003): CDA ●**Shuttle-Mir MEEP/ODC Aerogels retrieved**
1998	●Nozomi launch (∼2004): MDC ●Leonid MAC (∼1999): HD-TV flux & Meteoric cloud observation	●*MGS Phobos close-up* ●Galileo Jupiter Gossamer Ring flyby ●*Galileo Jovian small inner satellites flyby (Metis, Adrastea, Amalthea, and Thebe)* ●Deep Space-1 launch (∼1999+): No ●Leonid meteoroid shower (∼2002): MAC ●ISS construction starts (∼2003) ●*NEAR Eros flyby*
1999	●**JARE-39 AMMs arrive Japan** ●JARE-41 (∼2001):2nd AMM expedition	●STARDUST launch (∼2006): Aerogel, CIDA, DFM ●*Deep Space-1 Braille flyby*
2000		●*NEAR Eros rendezvous* ●STARDUST interstellar dust collection-1
2001	●**JARE-41 AMMs arrive Japan** ●**ISS-Russian Service Module aerogel samples return to Earth (∼2003): MPAC**	(●Genesis launch (∼2003): No) ●*DS-1 possible extended mission to fly-by Comets Wilson-Harrington & Borrelly*
2002	●MUSES-C launch (∼2006): No ●JEM-EF operation starts (∼2012): SEDA/MPAC	●CONTOUR launch (∼2008): CIDA ●STARDUST interstellar dust collection-2
2003	●*MUSES-C arrives Nereus or 1989ML; Surface material sampling* ●*Nozomi arrives Mars; Detection of Martian dust torus near Phobos and Deimos* ●**JEM-EF SEDA/MPAC samples return to Earth** (●Lunar-A launch (∼2004): No) (●SELENE launch (∼2004): No)	●*CONTOUR Comet Encke flyby* ●Rosetta launch (∼2011): DFA, CIDA, COSIMA ●Cassini/Huygens arrives Saturn/Titan (●**Genesis Solar Wind Particle samples return to Earth**)
2004		●Deep Impact Launch (∼2005): CIDA ●*STARDUST Comet Wild-2 flyby*; Cometary dust collection
2005	●Mercury Orbiter launch (∼2008): Hybrid Dust Detector, MOS	(●Mars Sample Return launch (∼2008): No?) ●Deep Impact Comet Tempel-1 encounter
2006	●**MUSES-C samples return to Earth**	●**STARDUST samples return to Earth** ●*CONTOUR Comet Schwassman-Wachmann-3 flyby*
2007		●Rosetta Mimistrobell flyby
2008	●Mercury Orbiter arrives Mercury	●*CONTOUR Comet d'Arrest flyby* ●*Rosetta Shipka flyby* ●(**Mars samples return to Earth**)
2009		
2010		
2011		●*Rosetta Comet Wirtanen rendezvous*
2012		●*Rosetta Comet Wirtanen landing*

Table 2. Opportunities for cosmic dust studies and parent body sample returns in 1996–2012 (as of November, 1999). Italics indicate the Japanese contributions.

Research Strategies	Missions/Spacecraft
Active In-situ Cosmic Dust Measurements in the Interplanetary Space (9)	●Galileo (Jupiter) ●Ulysses (Solar System Halo) ●Cassini (Saturn) ●*Nozomi (Mars)* ●STARDUST (Comet) ●CONTOUR (Comets) ●Rosetta (Comet and NEOs) ●Deep Impact (Comet) ●*ISAS Mercury Orbiter (Mercury)*
Major Passive In-situ Cosmic Dust Collections and Post Flight Analyses in LEO (4)	●*SFU-PFA* ●Mir-MEEP/ODC ●HST-PFA #3 ●*ISS-JEM-EF-SEDA/MPAC*
Parent Body Sample Returns (2)	●STARDUST ●*MUSES-C*

the advancement of the human space activities. Especially in the next 15 years, one of the major focal interests in the planetary exploration is minor bodies in association with the local dust environment of different parts of the Solar System. Table 1 summarizes currently funded/selected missions for such studies as well as sample return opportunities of micrometeoroids and micrometeorites both in the Japanese and international space programs. In 1996–2012, up to 8 comets and 12 asteroids (including 6 small satellites of Mars and Jupiter) will be visited, two of which are planned for sample returns (see the later section for more details); 9 interplanetary space probes will conduct active dust measurements in the various parts of the Solar System from the orbit of Mercury to that of Saturn; 4 major passive dust collection or post flight impact investigations in the LEO are also in progress or in preparation (Table 2). It is clear that the importance and thus also research opportunities in in-situ measurements and collection of cosmic dust will increase as these programs will be carried out. The Japanese scientific community is expected to contribute this field, too.

From the start of the space shuttle era, post flight analyses (PFA) of retrieved components or whole bodies of large and long exposure spacecraft have been carried out. Their list includes NASA's Solar Maximum Mission satellite (SMM) (Warren *et al.*, 1989) and Long Duration Exposure Facility (LDEF) (See *et al.*, 1990), ESA's European Retrievable Carrier (EuReCa) (UniSpace Kent *et al.*, 1994), and the Hubble Space Telescope (HST) solar cell array (SCA) of NASA and ESA (Space Application Services *et al.*, 1995; Yano, 1995). Together with laboratory experiments and computer simulations of hypervelocity impacts to correlate between crater and impactor dimensions, they provided abundant data and revised our insights of the microparticulate environment in the LEO. For instance, the LDEF data enabled to estimate the current annual accretion rate of extraterrestrial materials as $(40 \pm 20) \times 10^3$ tons with a peak of $\sim$200 μm diameter (Love and Brownlee, 1993) while the flux of the meteoroids

that left residues of analyzable size for the energy dispersive X-ray analyzer (EDX) inside the crater on metal targets exceeds non-aluminium orbital debris at the ratio of $\sim$9:5 (Yano, 1995).

2. SFU-Post Flight Analysis
2.1 General overview

The PFA of Japan's first retrievable satellite Space Flyer Unit (SFU) follows this "lineage" to better understand the LEO dust environment (Kuriki *et al.*, 1997). Launched by the H-II rocket in March 1995, SFU was retrieved in January 1996 during the space shuttle mission STS-72 (Fig. 1). The spacecraft had orbited the Earth at an operational altitude of $\sim$480 km and an inclination of 28.5° in a total of 301 days. It had an octagonal cross section of $\sim$4.5 m in diameter by 3.0 m height. Its total exposed area was $\sim$146 m^2 although its two solar arrays of $\sim$50 m^2 each were jettisoned due to a failure of latching signals during its retrieval (Fig. 2). Except for its first month, devoted to an infrared telescope operation, its attitude control was such that solar cells always faced to the Sun while one of the solar array paddles pointed to the ecliptic northern hemisphere. Thus there was a face (+Z) preferentially headed to the apex of the Earth's heliocentric motion. This makes the direction of orbital debris impacts, which are bound to the geocentric co-ordinates, to appear randomized.

The SFU-PFA focused on large, flat surfaces made of uniform components with a small influence of local shielding by other parts of the spacecraft body. Its systematic impact flux studies included (1) aluminized Kapton multi-layer insulation (MLI) made of 12 layers of Kapton films and Dacron nets (Fig. 3a), (2) silvered Teflon radiators glued on 2024-T81 Al plate (second surface mirrors [SSM]; Fig. 3b), on peripheral, Sun-pointing and anti-Sun faces and, (3) painted Al plates like scuff plates and external panels of some experiments.

In a total of $\sim$28 m^2 scanned area, over 700 hypervelocity impact signatures were discovered and recorded. It includes
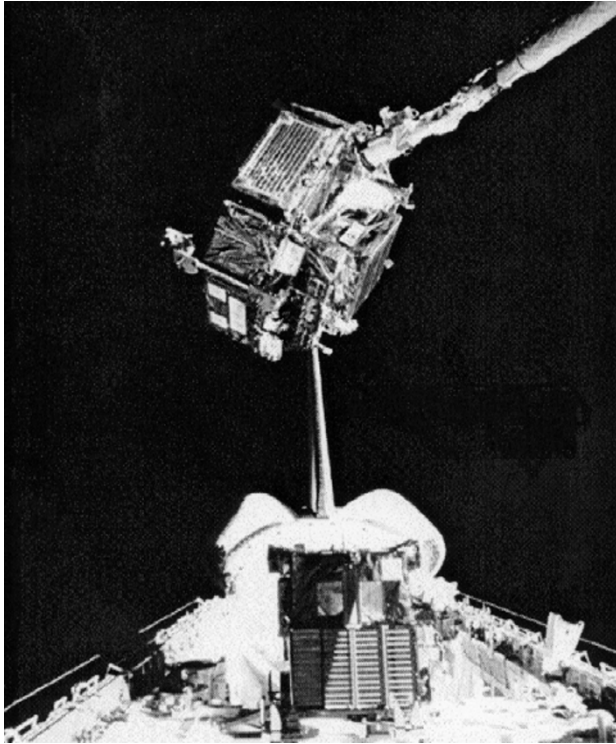
Fig. 1. Space Flyer Unit spacecraft at its retrieval in the STS-72 (Photo Courtesy: NASA).

Fig. 2. SFU configuration (solar cell arrays folded) viewed from the Sun pointing face.

a "clustered streak" of ∼50 hypervelocity impact holes concentrated in some 100 cm² area on a MLI near a reaction control system (RCS) thruster, possibly due to the secondary impact ejecta.

Impact craters on SSMs and penetration holes on MLIs were studied in detail on their morphological types, size-dependent fluxes and elemental compositions of their impact residues. Details of the PFA operation including the contamination control and the initial findings were reported elsewhere (Deshpande *et al.*, 1997a; Yano *et al.*, 1997; Kibe *et al.*, 1997). By using X-ray CT scan and laser microscope, three dimensional analysis of impact crater profiles on the SSMs and the number of penetrated layers of the MLIs were also studied to constrain physical parameters of impactors (i.e., size, density, impact velocity, etc.) (Morishige *et al.*, 1999; Yano *et al.*, 1999). The SSM impact craters were classified into four types (A∼D) depending upon degree of damages (Kibe *et al.*, 1997).

Cross calibration tests for the same materials used for the SSM, MLI, Al alloys and solar cells have been carried out on a light gas gun at ∼5 km/s (Neish *et al.*, 1997) and the Van de Graaff accelerator at ∼10 km/s. In compliance with the agreement made in the Inter-Agency Debris Coordination (IADC) group by major space agencies all over the world to exchange information and to promote collaboration in the meteoroid and debris research, the initial data have been made available to public and continuously updated in the "SFU Meteoroids and Debris Data Archive" homepage at the URL http://www.nal.go.jp/www-e/juuten/kyoten/SFU/SFU.html (Deshpande *et al.*, 1997b).
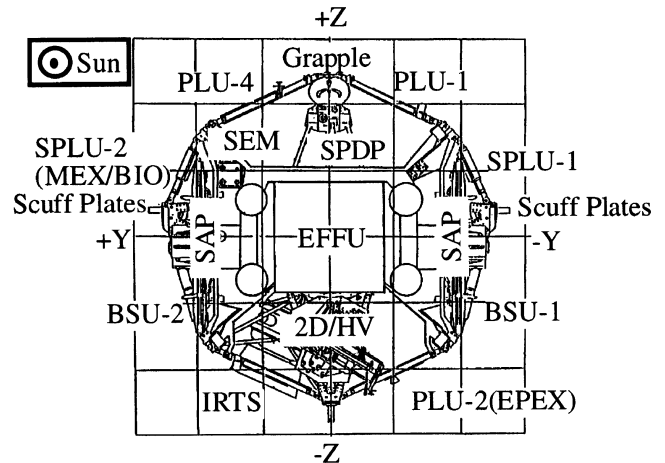
2.2 Elemental analysis of impactor residues

Semi-qualitative elemental analysis of residues on the SSMs and MLIs were conducted to determine origins of the impactors by using the JEOL JSM 5310LV system, a low vacuum-scanning electron microscope (LV-SEM) and EDX, which did not require conductive coating for imaging such that samples for subsequent detail analyses would not suffer from artificial contamination and deposition (Yano *et al.*, 1998). For routine scanning, its acceleration voltage was 15 kV in 20 Pa vacuum level and collection time was 100 seconds. All sites were sampled inside, lip and outside of impact craters or holes and judged from the all the data combined. As for the MLI, each penetration was examined the impact lip and its surroundings on the "back" side of the "top" layer and the "front" side of the "bottom" layer that impactor remnants and molten fragments of upper layers were deposited in order to avoid counting the surface contamination. To be consistent with chemical analyses of the previous spacecraft PFAs, the analysis also adapted the classification of major spectra for meteoroids and debris proposed for the LDEF Al clamps and intercostals (Zolensky *et al.*, 1993) and the EuReCa Al foils (Yano *et al.*, 1996), except any peaks produced by background materials, such as F and C for the Teflon SSM, C and O for the Kapton MLI with Cu and Zn for brass sample holders. Also excluded were Al and Si for the large SSM impacts which craters reached to the Al substrate and the Si-based adhesive underneath the Teflon layer.

Figure 3 shows a LV-SEM/EDX image and spectra of a typical micrometeoroid (M) impact. With M and orbital debris (D) origins, impacts were classified into four more categories. "FeS-Si" means that impacts indicate only these three elements, which might well be metallic sulfide meteoroids although S was occasionally included in terrestrial contamination so that it could also be steel debris. "No Residues (N)" means that impacts left no residues large enough to be detected by SEM/EDX. "Undetermined (U)" is a class that indicated several peaks but lacked or added some elements in order to be judged their origins. This might be due to depletion or fractionation of particular elements by melting and vaporization of the impactors. "Contamination Only
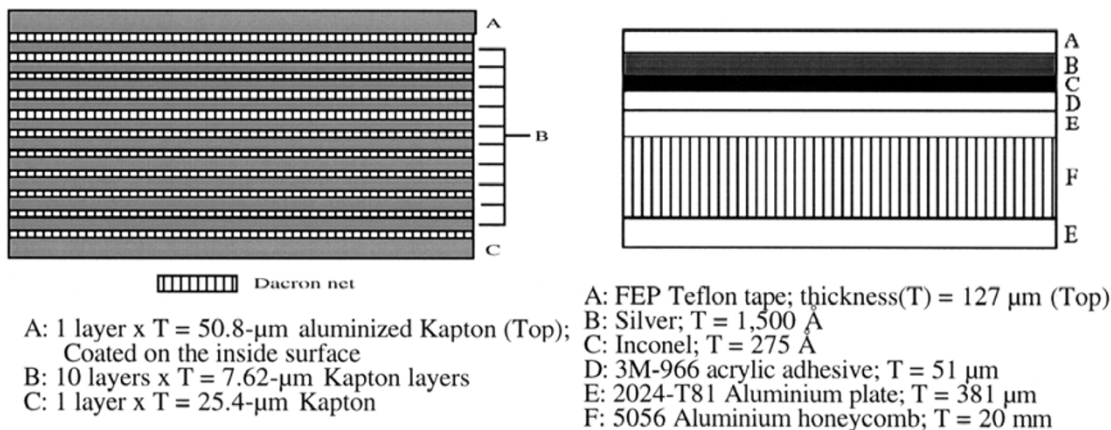
A: 1 layer x T = 50.8-μm aluminized Kapton (Top);
  Coated on the inside surface
B: 10 layers x T = 7.62-μm Kapton layers
C: 1 layer x T = 25.4-μm Kapton

A: FEP Teflon tape; thickness(T) = 127 μm (Top)
B: Silver; T = 1,500 Å
C: Inconel; T = 275 Å
D: 3M-966 acrylic adhesive; T = 51 μm
E: 2024-T81 Aluminium plate; T = 381 μm
F: 5056 Aluminium honeycomb; T = 20 mm

Fig. 3. Schematics of cross-section of (left) the multi-layer insulation (MLI) and (right) second surface mirrors (SSM) of the SFU spacecraft.
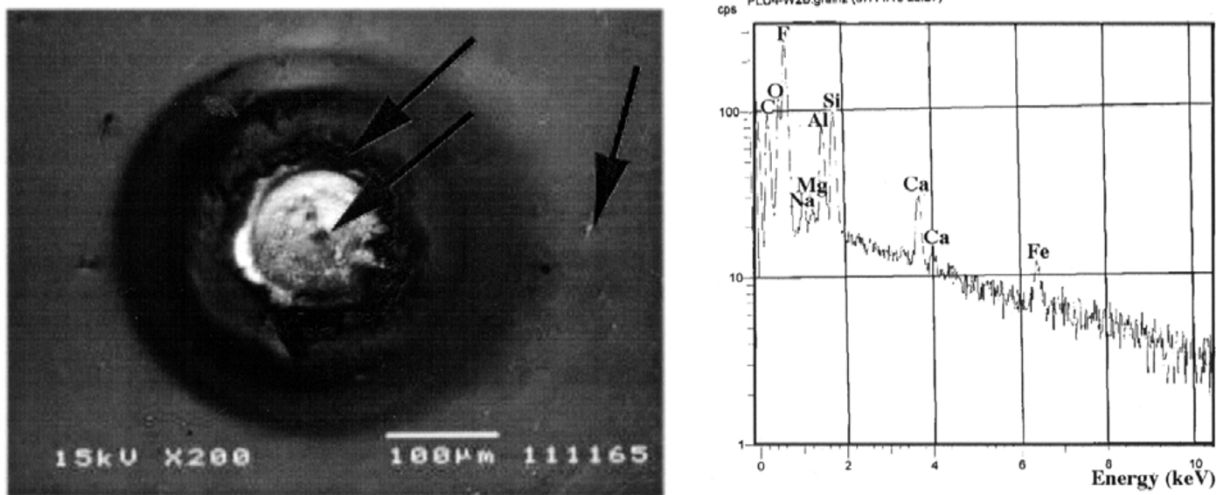
Fig. 4. SEM image and EDX spectra indicating meteoritic features of the SSM crater PLU4-W2B. Arrows indicate inside the crater, on the lip and on a flat target surface outside the crater, where the spectrum were acquired to distinguish real residue signals from the background contamination. The spectra above was taken from the central region of the crater bottom.

(C)" means that craters indicate only elements coming from contaminants; it is a "contaminated N class". Typical contamination for the SSM surfaces were Na and K associated with Cl. If Cl is missing, they might be solid Na/K droplet debris like ROSAT coolant leak (though in a different altitude). However one cannot rule out sea breeze formed salt crystals inside the craters after the landing as observed on the LDEF surfaces (Bernhard *et al.*, 1995). If P and S were present (Carbon could not be separated from background), they might be faster impacts of waste dump from the space shuttle orbiter during the SFU retrieval; Deshpande *et al.* (1997a) found several "liquid splash" marks, indicative of slow impact by such droplets, with these elements on the SSM surface.

In total of the 114 SSM impacts, 11 Al fragments, 6 Stainless steels, and 1 Ti paint flake were identified for the D class. Combined with the three-dimensional analysis, it was found that denser debris (e.g., stainless steel) formed deeper craters than less dense ones (e.g., Al). However it should be

reminded that all the Al fragments could be identified in small craters that penetrated the top Teflon layer only, but did not reach to the Al substrate. Stainless steel debris were found in all the crater types regardless their sizes and depths. Consequently, meteoroids and debris shared 7.0% and 15.8%, respectively, with 1.8% of FeS-Si among the SSM impacts (Fig. 4; Yano *et al.*, 1999). These numbers should be regarded as the lower limit of the ratio of each class.

For the MLIs, of ~384 impacts in 10.4 m² scanned area, only a few impacts were perforated all the layers proving the MLI worked as an efficient "capture cell" to trap impactor residues inside (Fig. 5). LV-SEM/EDX analysis was performed for 56 MLI impacts on the Sun-pointing, Anti-Sun and peripheral (Earth's Anti-apex) faces (Fig. 6). Though the sampling numbers are low in the Sun and Anti-Sun faces, the meteoroid to debris ratios on the Sun and peripheral faces were similar to each other. This is not surprising because both faces receive randomized debris components and sporadic meteoroids equally, but do not have flux enhancements
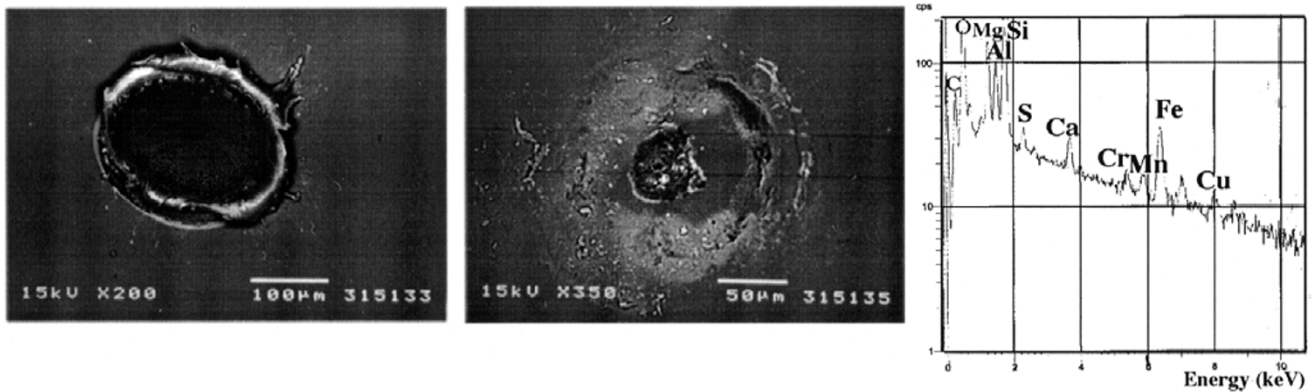
Fig. 5. SEM images of the back side of the top layer (above left) and the front side of the fourth layer with residues (above right) of MLI penetration PLU2-m2-24 and its EDX spectra showing meteoritic features (right).
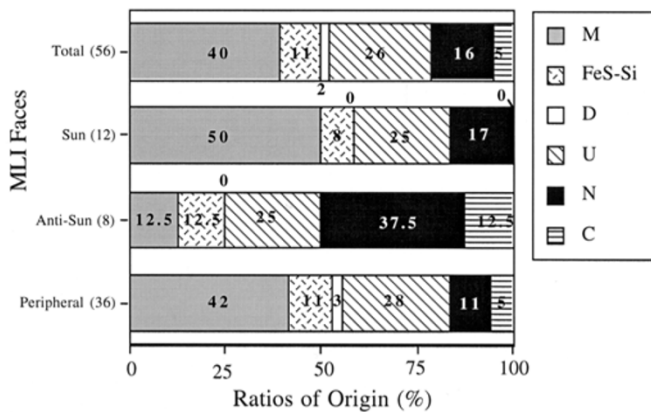

Fig. 6. Ratios of the origin of MLI impactors by pointing faces. ( ) indicates the number of samples. Keys = M: meteoroids, D = orbital debris, U: undetermined, N: no residues,m C: contamination only.

of meteoroids from the Earth apex. However, it must be noted that the MLI film was coated with Al so that we could not identify Al-based debris, which was the majority of the D class for the SSM impacts. Thus some Al-based debris might have been included within the N class. Also noted was that there were more FeS-Si impacts than the SSM. The FeS-Si inside MLI is most likely to be metallic sulfide meteoroids than Fe-based debris because there was much less contamination (C) included sulfur inside the MLI than the SSM surface. Indeed, Graham *et al.* (1997) classified this type as plymineralic meteoroid impacts on their HST solar cell cover glass samples by using back-scattered electron and X-ray imagery. In total, the MLI holds M for 39.3% with FeS-Si for 10.7%, (non Al-based) D for 1.8%, and N for 16.1%.

Figure 7 and Table 3 compare SFU with elemental analyses of the previous spacecraft impacts from 1980–1993. The CIMMS (Chemical and Isotopic Measurements of Micrometeoroids using SIMS) experiment on LDEF utilized a secondary ion mass spectrometer (SIMS) to investigate the EDX-N class and enabled ~95% of them to be determined origins (Amari *et al.*, 1993). It proved that LDEF received mostly natural impacts on the trailing face (west) and de-

bris on the leading face (east). Except the LDEF CIMMS and HST cells described above, the rest were analysed by SEM/EDX (Yano, 1995). As a result, roughly about a half of impacts were unknown origin while meteoroids were found in a range of 10 ~ 30%. For the SFU-MLI, it goes up to ~50% if M and FeS-Si are combined. And even if we assume that all the N and C classes are due to debris impacts, natural origin still exceeds them, at least in the range of hole diameter (Dh) of 51–748 μm. In reality, some of N impacts may be natural origin which did not leave any residues due to too high impact velocity or/and volatile components like cometary grains. Laboratory experiments demonstrated that more than 90% of 50–100 μm sized micrometeorites from Antarctic ice cores survived impacts on thick Al plates at ~5 km/s and left sizable residues without any significant elemental depletion (Yano *et al.*, 1996). This implies that, if these U and N impacts were due to "chondritic" type micrometeoroids which were originally similar to ones found in the Antarctic ice cores (e.g., Maurette *et al.*, 1994) but depleted relatively light elements like Mg and S during their impacts on SFU, their impact velocities must have been significantly faster than ~5 km/s. This scenario favors comets (especially ones with a retrograde orbit) as the origin of these microparticles, rather than main belt asteroids, as some previous studies also suggested (e.g., Graham *et al.*, 1998).

2.3 Time variation of impact flux

Figure 8 compares the impact flux of SFU with those of LDEF, EuReCa, and HST all in the Sun-pointing faces, which were converted their impact crater diameters to Fmax, the equivalent maximum thickness of an aluminium plate for marginal perforation to be occurred by a non-oblique hypervelocity impact (Yano *et al.*, 1999). We adopted each of Fmax conversion factor for Dh on the LDEF Al foils by McDonnell and Sullivan (1992), for inner crater diameter (Dc) on the LDEF Al thick targets by Yano (1995), and for conchoidal fracture diameter (Dco) on the EuReCa and HST solar cell cover glasses by Taylor *et al.*, (1999), respectively. Although a largely accepted empirical conversion factors of Kapton to Fmax is not yet available, the SFU-MLI data was plotted with Dh as a reference because our cross calibration impact experiments up to ~5 km/s showed that the Kapton Dh sizes do not exceed the Al Fmax within a factor of ~5
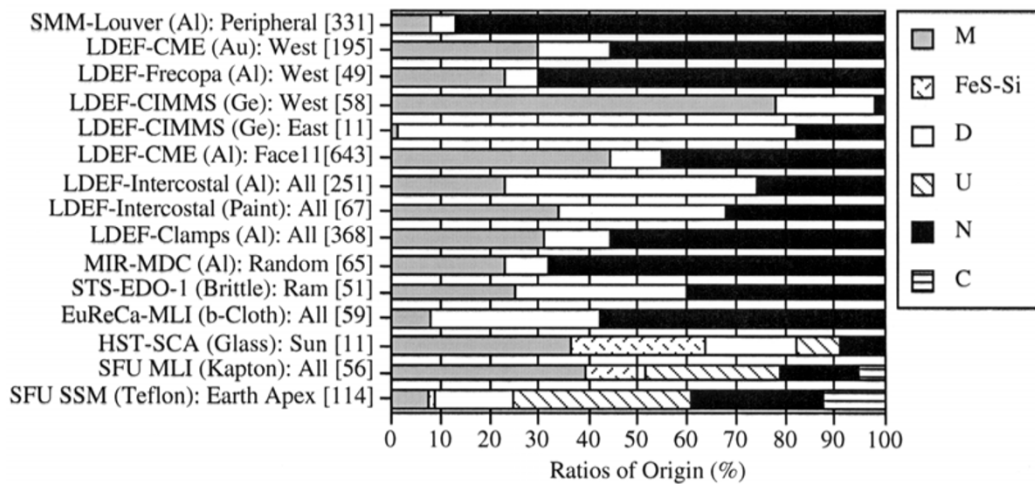
Fig. 7. Summary of ratios of impactor origins of retrieved spacecraft judged by elemental analyses. For details, refer Table 3. From left to right, each column shows spacecraft-experiment/exposed surface (target material): facing direction [number of samples].

Table 3. Classifications and ratios of impactor origins of experiments and PFAs of exposed surfaces on the retrieved spacecraft in the past, judged by EDX elemental analyses (∗ = except CIMMS which were examined by SIMS). HST and SFU are adopted from Graham *et al.* (1997) and SFU data from Yano *et al.* (1999), respectively. The rest were compiled by Yano (1995).

Spacecraft	Experiment/ Surface	Target Material	Pointing Direction	Total No. Samples	M (%)	FeS-Si (%)	D (%)	U (%)	N (%)	C (%)
SMM	Louver	Al	Peripheral	331	8		5		87	
LDEF	CME	Au	West	195	30		14		56	
		Al	Face 11	643	44		11		45	
	Frecopa		West	49	23		7		70	
	CIMMS*	Ge		58	78		20		2	
			East	11	1		81		18	
	Intercostal	Painted Al	All	67	34		34		32	
		Al		251	23		51		26	
	Clamps			368	31		13		56	
MIR	MDC	Al	Random	65	23		9		68	
STS	EDO-1	Brittle	Ram	51	25		35		40	
EuReCa	MLI	β-Cloth	All	59	8		34		58	
HST	Solar Cells	Glass	Sun	11	36.4	27.3	18.2	9.1	9.1	0.0
SFU	MLI	Kapton	All	56	39.3	10.7	1.8	26.8	16.1	5.4
	SSM	Teflon	Earth Apex	114	7	1.8	15.8	36.0	27.2	12.3

including the maximum error range. Permitting this limitation that may leads a slight shift along the X-axis, all the four spacecraft match their mass distribution index in the size regime of the SFU MLI Dh. For the smaller regions, LDEF flux exceeds EuReCa and HST, both of which agree with each other in the error range. This means that as large impacts at Fmax >~50 μm, where meteoroids are expected to exceed debris population from the model prediction, seem to have constant fluxes in 1984–1996, whereas the flux of smaller impacts at Fmax <~50 μm in the median epoch of 1984–1990 seems up to a factor of ~4 higher than that in

the median epochs of 1989–1993 and of 1992–1993. One possible explanation of this is that small debris exceeding meteoroid flux in the size regime were shortened their orbital lifetimes and deorbited by the expanded upper atmosphere during the last solar activity maximum at a peak of 1990 (see a related work by McDonnell *et al.*, 1997).

3. Aerogel Exposure on a Space Shuttle Orbiter

As already stated, there are still about a half of microcraters on the past retrieved spacecraft that left no analyzable residues within EDX sensitivity limits and therefore the
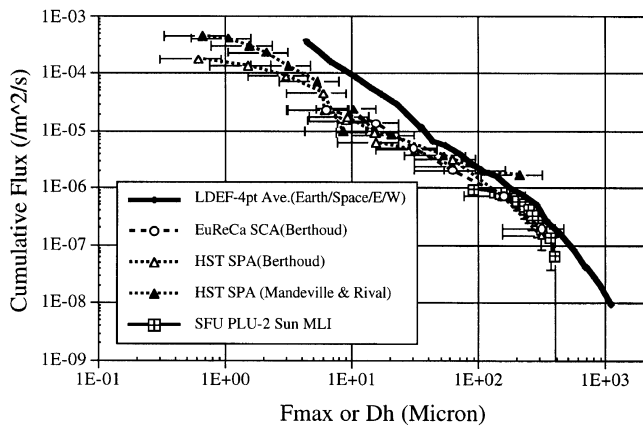
Fig. 8. Comparison of impact fluxes on the Sun pointing faces of LDEF, EuReCa, HST and SFU. All but SFU (MLI Dh) were converted to Fmax (μm), the maximum thickness of an aluminium plate for marginal performance due to hypervelocity impacts. Empirical conversion formulae were adopted from McDonnell and Sullivan (1992), Yano (1995) and Taylor et al. (1999).

Fig. 9. MFD-ESEM dust collector made of aerogel which was on-board the STS-85 mission (Photo courtesy: NASDA).

corrected ratio between meteoroids and debris is yet undetermined. Following opportunistic PFAs for studying origins of microparticles, intact capture of meteoroids and debris with the least destructive fashion is the next logical step for subsequent analyses of elements, mineralogy, petrology, size, structure and bulk density of the captured particles. Since the early 1990's, ultra-low dense materials such as micropore foams and amorphous silica aerogels were deployed in space on-board the space shuttle orbiter (e.g., Maag and Linder, 1992; Tsou, 1995), the EuReCa satellite (e.g., Brownlee et al., 1994; Burchell et al., 1999) and Mir Space Station (e.g., Hörz et al., 1998). Being optically transparent (easy to locate and extract trapped particles), of very low density (0.1–0.01 g/cm^3), but nevertheless proven in the space environment (robust against vacuum and extreme temperatures: thermal conductivity of $\sim$15 mW/m-K at 1 atm), aerogel has been used more often than micropore foam. Also the aerogel is high purity SiO$_2$ which does not severely harm post retrieval chemical analysis and capsulates trapped particles which are kept relatively uncontaminated. These advantages have made aerogels to be used as a collection medium for cometary and interstellar dust grains by the STARDUST mission (Vellinga et al., 1997).

During the space shuttle STS-85 mission in August 7–19, 1997, the National Space Development Agencies of Japan (NASDA) flew four modules of 10 cm × 10 cm area with 2 cm depth made of aerogel blocks with 0.030$\pm$0.005 g/cm^3 density in a stack of four layers, as a part of the Manipulator Flight Demonstration (MFD)—Evaluation of Space Environment and Effects on Materials (ESEM) experiment (Fig. 9; Kitazawa et al., 1998a). It was located alongside of the MFD pallet and exposed at 316 km altitude and 51.7° inclination for about 12 days in total and for 54 hours facing to the velocity vector of the orbiter. After its PFA, no hypervelocity impact signatures were found in the exposed surface. It was not surprising due to its too short mission duration and small exposed area. Only two impactors which apparently hit the aerogel module at extremely low veloci-
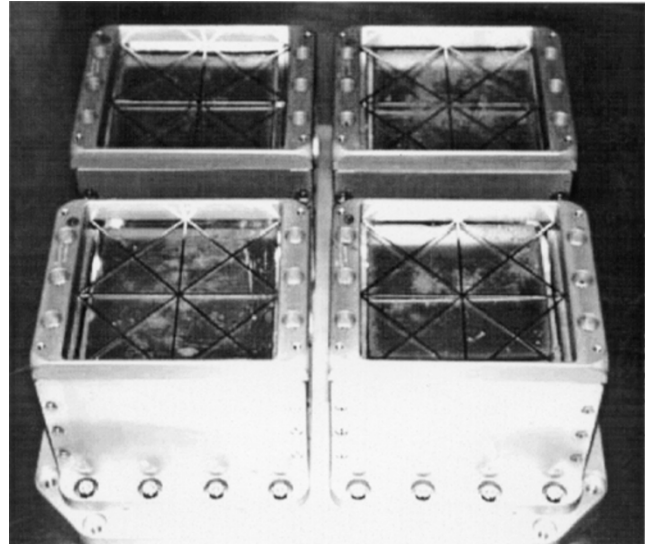
ties were discovered. Morphological and elemental analyses suggested that they were debris particles emitted from the shuttle orbiter or/and its other exposed experiments (i.e., not another shuttle mission nor other spacecraft) (Kitazawa et al., 1998a).

4. An Exposed Payload for the International Space Station

On the other hand, the MFD-ESEM has proven its spaceflight qualification and led to develop a new Microparticle Capturer (MPAC) module as a part of the Space Environment Data Acquisition Equipment (SEDA), one of the very first four payloads of the Japanese Experiment Module (JEM)—Exposed Facility (EF) on the International Space Station (ISS) (Fig. 10; Kitazawa et al., 1998b). The MPAC is yet another passive dust collector made of the same aerogels and other "space-proven" target materials such as Al alloy and gold plates enabling for direct comparison with the previous spacecraft PFA. At this time, the target will be exposed in the ISS operational altitude up to 1 $\sim$ 3 years from the year 2002 and be retrieved back to the Earth for subsequent laboratory analyses. Larger MPAC aerogel modules will also be exposed on the exterior of the ISS Russian Service module from 2001 and one third of the portion will be returned to Earth every year in the total duration of 3 years.

5. Hybrid Dust Collector and Detector

Previous PFAs and simple passive collectors are low-cost, well-established space-proven technology which enable researchers to study impact sites of microparticles with state-of-the-art analytical instruments at ground laboratories. However, their severe disadvantage in terms of to understanding origins of impactors is that they normally can reveal only very limited information of impactors (size and composition in some cases), number of impacts which have impact fluxes averaged out over the integrated exposure time, and impact angles in limited cases. They can hardly retain unambiguous information regarding the impact trajectory, impact velocity,
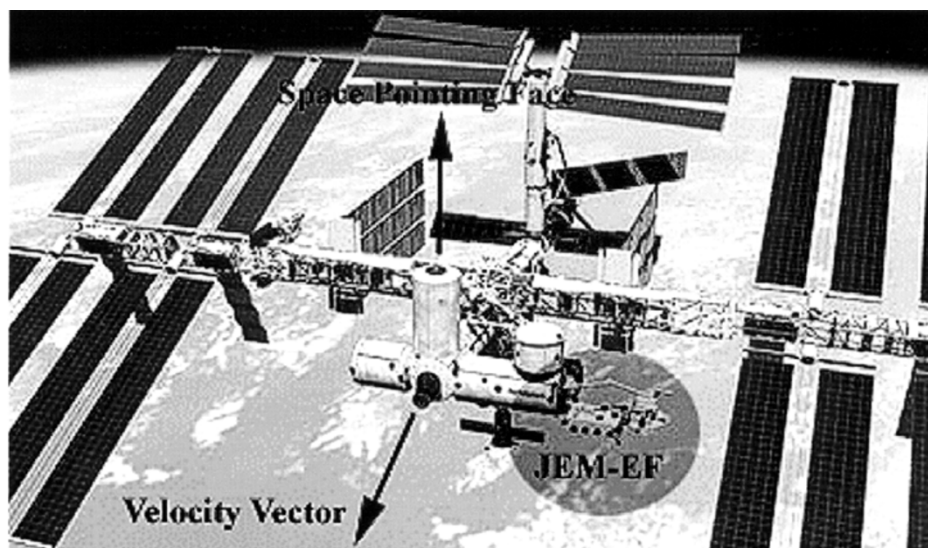
Fig. 10. An artist impression of the JEM-EF on the ISS. Note that the Exposed Facility has open field of views not only to the velocity vector but also to the space and trailing faces where meteoroids can be preferentially collected (Computer Graphic Courtesy: NASA).

impactor mass and shape, and time of impacts, all of which are important parameters to separate meteoroids from orbital debris as well as sub-divide the natural impacts by their parent bodies, i.e., asteroids vs. comets. In fact, active detectors on-board LDEF and the Mir Space Station clearly show that there occur very high flux events such as debris swarms and seasonal meteoroid streams over a month-to-year time frame (Mulholland *et al.*, 1992; Maag *et al.*, 1997).

In order to get these information by in-situ instrumentation in space, there are two options to be pursued. One is real time active detectors being capable of time-of-flight mass spectrometer (TOF-MS) for impact induced plasma to measure elements of impacting particles at the time of impact. Such instruments have been deployed on interplanetary probes such as Helios, Giotto, Vega and Cassini/Huygens and STARDUST spacecraft since 1970's and improved versions are prepared on-board the forthcoming CONTOUR and Rosetta missions. Although potentially being useful to measure flux ratio between meteoroids and space debris, no TOF-MS has been utilized for measurement of the near-Earth dust environment so far.

The other option is a dust collector with time resolved function. Several attempts for this concept were made in the past. The Timeband Capture Cell Experiment (TiCCE) was deployed on EuReCa in 1992–1993 (Stevenson, 1988). It was designed to backdate time of impacts from distances between penetration holes on a top thin foil and impact residues on the witness plates underneath along the movement of guiding wires shifted at a constant rate (several mm per a few days) over the mission. However it was malfunctioned after its first few steps. On the Mir station, "suit-case" type aerogel dust collectors were exposed (Hörz *et al.*, 1998). It could control the exposed duration but did require astronauts to perform extra-vehicular activities (EVA) for opening and closing; thus its time resolution depended upon an interval of the two EVAs and it is not at all a flexible and economical option.
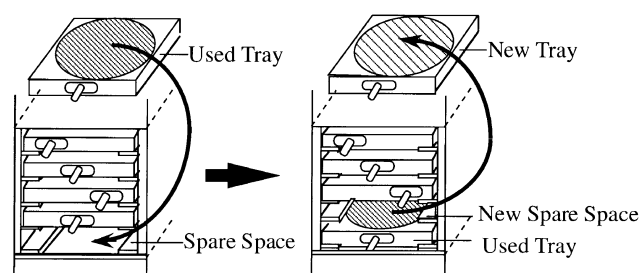

Fig. 11. A drawer-type dust collection system exchanged by the robot arm to expose fresh trays for specific high flux impact events with known origins.

For the ISS, scientists from its international partners also considered similar platforms for time-resolved, retrievable dust collectors with abundant resources on their exposed modules. They include the Cosmic Dust Collection Facility (CDCF) for the NASA Express Pallet (The Steering Committee for the CDCF, 1988), the Dust Watch pop-up system for the ESA-Columbus (Yano *et al.*, 1993), and the Cosmic Dust Collectors and Detectors (CDCD) drawer system (Fig. 11; Yano, 1994), rotating wheel (Fig. 12; Yano and Kitazawa, 1998) and smart passives (Yano and Kitazawa, 1998) for the JEM-EF. Among those, only the JEM-EF can provide in-orbit service capability by the robot arm at any given time such that high flux events from known origins can be selected for pre-installed trays, without requiring EVAs. The JEM-EF also provides four exposed faces with respect to the Earth gravity stabilized attitude control of the station (east, west, north and space) in the nominal operation duration of 10 years. The trailing and space faces are where meteoroid impacts exceed artificial debris, thus suitable to study and collect micrometeoroids efficiently.

After a review of the relative merits by Yano and Kitazawa (1998), the aerogel-based hybrid dust collector and detector (HD-CAD) was considered to be as the most favorable con-
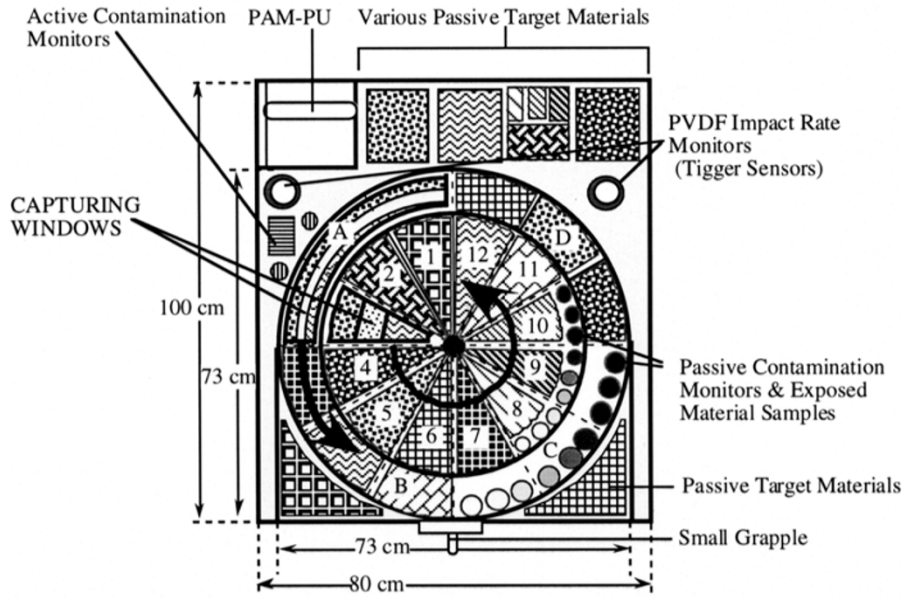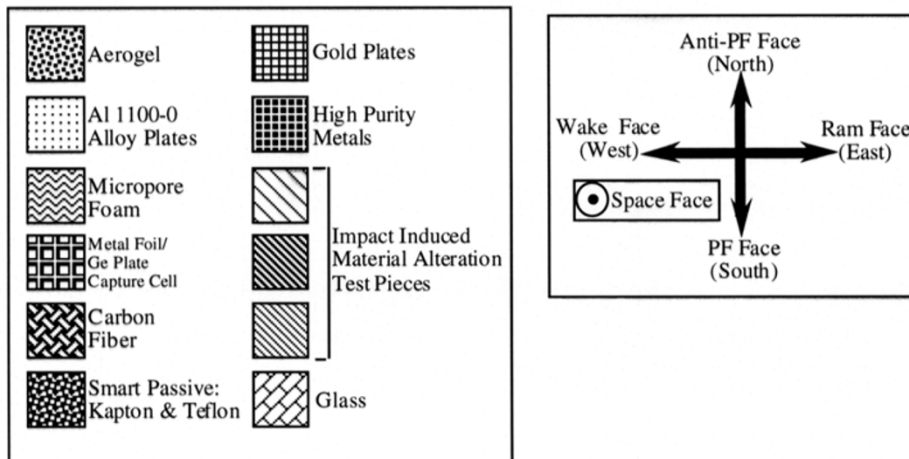
Fig. 12. Rotating wheel system designed for a JEM-EF payload on the space face with various exposed target materials. Keys: PF = pressurized facility; PVDF = polyvinylidene fluoride; PAM-PU = grapple bar for logistic pallet fixture.

cept to date. It measures the time of impact, energy and velocity (thus estimates mass) of impactors in real time while it still captures particles intact. The aerogel is also used as an impact target that produces impact flash to measure the time of such an event, intensity of flash light as a function of impact energy, its duration, and direction of track excavation. We can reconstruct therefore the impact trajectory by a two dimensional, position sensitive CCD arrays on the bottom and a pair of linear CCD arrays along the sides (Fig. 13). Velocity measurement can be made with both the side CCD arrays and discharge signals by penetration of thin polyvinylidene fluoride (PVDF) films (e.g., ~1 μm) with fast digital data processors (e.g., Nogami *et al.*, 1997). PVDF is a semicrystalline polymer that exhibits strong piezoelectric properties, which produce electric signals due to local mechanical stress, e.g., microparticulate impacts. Initial series of laboratory impact experiments successfully recorded such impact flashes

from the aerogels impacted by 25–50 μm glass and alumina projectiles at 4.2 ~ 4.6 km/s (Yano and Kitazawa, 1998).

The most important advantage of this system over other options is a wide variety of its application. This single system can be used for (1) long duration and continuous monitoring and intact capture of meteoroid and debris on-board LEO spacecraft such as JEM-EF; (2) sample return missions to parent bodies of meteoroids, i.e., comets and asteroids for capturing ejected particles from their surfaces as successors of STARDUST for comets (Vellinga *et al.*, 1997) and MUSES-C for near-Earth asteroids (Kawaguchi *et al.*, 1998) (see the next chapter); and (3) one-way planetary missions which employ an electric propulsion system or/and experience so harsh thermal and plasma environment that impact induced plasma detectors like TOF-MS may suffer from significant noise, such as a Mercury orbiter and a solar probe, as an impact flash detector.
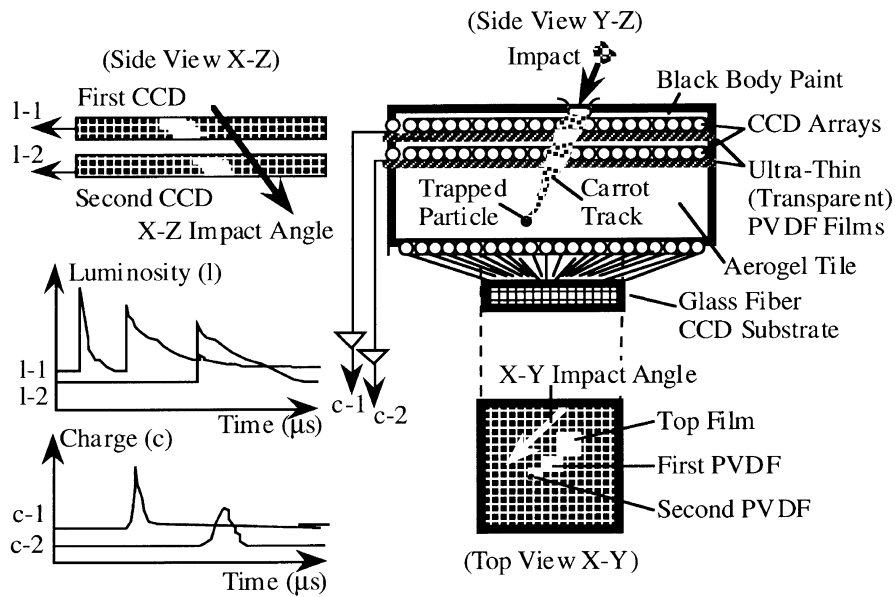
Fig. 13. Concept of the aerogel-based HD-CAD system.

6. Sample Return Missions to Parent Bodies

At present, there are hundreds of meteoroid impact craters on retrieved spacecraft components (Yano, 1995), thousands of stratospheric interplanetary dust particles (IDPs) (CDPET, 1982–1994), and some tens of thousands of micrometeorites from polar ice cores (Maurette et al., 1994) collected and studied in the respective curation systems. Some of them were even analyzed mineralogy. Yet we do not even know whether fractal aggregates of sub-micron monomers collected in the stratosphere and partially-melted micrometeorites from Antarctic ice cores share their origins or not. The ratio between asteroidal and cometary dust grains falling to the Earth remains an unsolved question, all because we have not had any dust samples with "ground truth", unambiguous answers of their origins. To achieve this goal and classify a collection of the micrometeoroid/meteorite samples with currently unknown origins, there are two sample return missions to small bodies being prepared: NASA's STARDUST for a comet and ISAS's MUSES-C for a near Earth asteroid. Both missions will collect small grains ejected from their parent bodies in the same mechanisms as their respective meteoroid productions: jetting of gas and dust flow for a comet nucleus (STARDUST) and ejection of spalled surface fragments by impacts for an asteroid (MUSES-C). Size ranges of the samples of both missions are similar to the micrometeoroid/meteorite samples so that consistent analytical procedure and techniques with them should be applied to the STARDUST and MUSES-C samples. Direct comparison of cometary and asteroidal dust grains with trapped meteoroids by the HD-CAD system in the LEO, thus unbiased by the Earth environment, will answer the above question.

7. Conclusions

Major results of the present studies and recent developments for future missions in the Japanese space program were reviewed regarding in-situ measurement and collection of micrometeoroids and orbital debris in the near Earth space.

The post flight impact analysis of the SFU satellite has been successfully conducted as its first kind in Japan and had over 700 actual space impact data fully documented. The impacts were classified into natural, man-made, unknown and undetermined origins. The results were consistent with the previously retrieved spacecraft but better records in successful identification of residue contents. The time variation of the microparticulate flux in the LEO seemed to vary from a stationary level where meteoroids exceeded debris to a significant decrease where debris exceeded meteoroids possibly due to shortening of their orbital life times by interaction with the upper atmosphere during the solar activity maximum.

However, it was recognized that in general for most of the retrieved spacecraft data in the past, about a half of impact craters on hard surfaces left no analyzable residues for EDX sensitivity, thus failing to decode the ratio between meteoroids and debris with high confidence. Therefore the next step was to develop intact capture technique for hypervelocity impacts. Following overseas experiments since 1990's, passive aerogel modules were exposed in LEO by NASDA in 1997. This experience led to design yet another microparticle collector to be on-board the ISS Russian service module and the JEM-EF from 2001.

The other disadvantage of the passive dust collectors, even including plain aerogel modules, is the inability to acquire finely time-resolved information and orbital parameters of impactors, which are as important as compositional analysis to determine their origins. Therefore the HD-CAD which overcomes these issues while still capturing particles intact has been introduced and currently been in the development phase. The system is suitable for both sample return missions in LEO as well as to parent bodies of meteoroids and one-way missions to where the thermal and plasma environment is such that impact induced plasma detectors may suffer from significant noise. Although technical challenges to develop this system have found to be not highly demanding (Yano and Kitazawa, 1998), clearly the availability of

impact simulation facilities for smaller sized and higher velocity impacts than what are available in the present Japanese institutions is the key for its successful realization. For this reason, recently a modification of the Van de Graaff electrostatic accelerator at the University of Tokyo has been made to enable solid, conductive microparticles to be accelerated (Hasegawa *et al.*, 1999). At the time of writing, this facility has achieved acceleration of conductive particles at 3-MV voltage, presently the highest level of this type of facility.

Despite the rich collection of micrometeoroid/meteorite samples for last 20 years, the ratio between asteroidal and cometary dust grains falling to the Earth still remains an unsolved question because there have no samples with unambiguous proof of their origins. To achieve this goal and classify these micrometeoroid/meteorites, currently planned sample return missions to a comet and an asteroid will play a vital role by direct comparison with trapped meteoroids by the HD-CAD system in the LEO.

Appendix A. List of Acronyms

AMM	Antarctic Micrometeorites
C	Contamination Only (EDX Analysis Classification)
CCD	Charged Couple Device
CDA	Cassini Dust Analyzer [Cassini]
CDCD	Cosmic Dust Collector/Detector [JEM-EF on ISS]
CDCF	Cosmic Dust Collection Facility [ISS]
CDPET	Cosmic Dust Preliminary Examination Team
CIDA	Cometary Impact Dust Analyzer [STARDUST]
CIMMS	Chemical and Isotopic Measurements of Micrometeoroids using SIMS [LDEF]
CONTOUR	Comet Nuclei Tour
COSIMA	Comet Secondary Ion Mass Analyzer [Rosetta]
D	Orbital Debris (EDX Analysis Classification)
DDS	Dust Detection System [Galileo]
DFA	Dust Flux Analyzer [Rosetta]
DFM	Dust Flux Monitor [STARDUST]
DS	Deep Space
EDX	Energy Dispersive X-ray Spectrum Analyzer
EF	Exposed Facility [JEM]
ESA	European Space Agency
ESEM	Evaluation of Space Environment and Effects on Materials [STS-85]

EuReCa	European Retrievable Carrier
EVA	Extra Vehicular Activity
FeS-Si	Iron, Sulfur and Silicate Bearing (EDX Analysis Classification)
HD-CAD	Hybrid Dust Collector and Detector
HST	Hubble Space Telescope
HD-TV	High Definition Television
IADC	Inter-Agency Debris Co-ordination Group
IDP	Interplanetary Dust Particles
ISAS	Institute of Space and Astronautical Science
ISS	International Space Station
JARE	Japan Antarctic Research Expedition
JEM	Japan Experiment Module
LDEF	Long Duration Exposure Facility
LEO	Low Earth Orbit
LV-SEM	Low Vacuum-Scanning Electron Microscope
M	Meteoroids (EDX Analysis Classification)
MAC	Multi-instrument Aircraft Campaign
MDC	Mars Dust Counter [Nozomi]
MEEP	Mir Environment Evaluation Package [Mir]
MFD	Manipulator Flight Demonstration [STS-85]
MGS	Mars Global Surveyor
MLI	Multi-Layer Insulation (or Insulator)
MOS	Metallic Oxide Silicon
MPAC	Microparticle Capturer [JEM-EF]
MUSES	Mu Rocket Series Space Engineering Satellite
N	No Residues (EDX Analysis Classification)
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NEAR	Near Earth Asteroid Rendezvous
NEDO	New Energy and Industrial Technology Development Organization
ODC	Orbital Debris Collector [Mir]
PFA	Post Flight Analysis
PVDF	Polyvinylidene Fluoride
RCS	Reaction Control System
SCA	Solar Cell Array
SEDA	Space Environment Data Acquisition System [JEM-EF]
SELENE	Selenological and Engineering Explorer
SEM	Scanning Electron Microscope
SFU	Space Flyer Unit
SIMS	Secondary Ion Mass Spectrometry
SMM	Solar Maximum Mission Satellite
SSM	Second Surface Mirrors [SFU]
STS	Space Transportation System
TiCCE	Timeband Capture Cell Experiment [EuReCa]
TOF-MS	Time-of-flight Mass Spectrometer
U	Undetermined (EDX Analysis Classification)
UDD	Ulysses Dust Detector [Ulysses]
USEF	The Institute for Unmanned Space Experiment Free Flyer

Appendix B. List of Nomenclature

Dc = inner crater diameter (mm - μm) [ductile target]

Dco = conchoidal fracture zone diameter (mm - μm) [brittle target]

Dh = penetration/perforation hole diameter (mm - μm)

Fmax = the equivalent maximum thickness of an aluminium plate for marginal perforation (mm - μm)

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