INTER-COMMISSION WORKING GROUP

ON THE PREVENTION OF INTERPLANETARY POLLUTION

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I. POLLUTION POTENTIALS IN INTERPLANETARY SPACE (C.S.L. Keay)

INTRODUCTION

At the 1988 Baltimore General Assembly of the International Astronomical Union, members of several Commissions dealing with planetary science expressed deep concern that no work was being undertaken to identify and avoid pollution problems in interplanetary space beyond the Moon. At that time NASA had convened a conference on problems in cislunar space due to the large and growing numbers of orbiting fragments hazardous to space vehicles. In translunar space this is hardly a problem. However an alarming number of future interplanetary mission proposals were considered for other reasons to be potentially harmful to various solar system bodies and interplanetary space itself.

Foremost among the problems identified at and soon after the Baltimore meeting were certain mission proposals for using either nuclear or kinetic energy to disrupt cometary nucleii and small asteroidal bodies. Concerns such as this led to the formation of a small working group under the leadership of I.P. Williams of the University of London. At the 21st General Assembly of the IAU in Buenos Aires, the group's report was made available to other interested parties for comment and criticism.

At the 1994 General Assembly at The Hague it was formally decided to establish a broader panel within the Planetary Systems Division of the IAU, with members drawn from six interested Commissions. Its title is the Working Group on the Prevention of Interplanetary Pollution and C.S.L. Keay was nominated as its Convenor. Membership includes astronomers from Australia, China, the Czech Republic, France, Japan, Russia and the United States of America.

During the course of the Working Group's discussions, several members baulked at the title of the body. It is clear that this should have been a Working Group on the Minimisation of Interplanetary Pollution and the title amended accordingly. However such a change is too late since this is a Final Report of the Working Group, recommending future actions to be discussed at the forthcoming IAU General Assembly in Kyoto, Japan, in 1997 August.

THE MAIN AREAS OF CONCERN

The first Working Group identified six principal areas of concern:

1. **Environmentally harmful propellant residues.** Heavy element propellants such as argon or mercury used in ion engines can contaminate surfaces up to 100,000 km distant, compromising future surface sampling (eg. for determination of isotope ratios). Cold nitrogen (from small

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thrusters) and steam (from rocket exhausts) are examples of benign propellants. On the other hand solid-fuel rockets, which produce large amounts of aluminium oxide in their exhausts, can significantly add to the number of light scatterers in the vicinity and compromise optical observations.

2. **Unconfined debris from impacting objects.** Members of Commission 21, which among other things is concerned with measuring zodiacal light, fear that the density of interplanetary dust in the inner solar system could easily be doubled by the impact of a one tonne probe striking a cometary nucleus head-on. On the other hand this is not a severe problem for giant planets, as the impacts of the Comet Shoemaker-Levy fragments on Jupiter proved. The contamination will gradually be diluted to the point where it merges with earlier impact debris to augment minor constituents in the Jovian atmosphere. However it is a different situation for small objects without an atmosphere where contamination by man-made objects may leave much more appreciable residues unacceptable for future surface studies.

3. **Radionuclide pollution from nuclear power generators.** If such generators are carried on a vehicle which subsequently impacts any object other than a giant planet, the consequences could be exceedingly serious. As this is being written, about one hundred demonstrators are gathered at the Kennedy Space Centre protesting at the inclusion of a nuclear power generator on the forthcoming Cassini mission to Saturn. Such generators can greatly reduce the total mass and cost of many missions, not least any future attempt to land men on Mars. It is therefore vital that sensible environmental impact assessments be made prior to commitments to employ nuclear power generators for power generation in space.

4. **Pollution from explosives, particularly nuclear.** Again the potential to increase the density of light-scatterers in interplanetary space must be carefully evaluated, as with their surface contamination consequences.

5. **Undesirable transfers of surface materials.** Mass transfer schemes have been mooted for delivering material for the construction of space habitats and other projects. The launch velocity tolerances for non-spillage of material at the collection points require careful analysis, and not be exceeded. Otherwise the spillage may cause damage elsewhere or could return later as a hazard to the completed project.

6. **Biocontamination prevention and quarantine measures.** Of all the areas of concern, this has been the most thoroughly studied to date, particularly in relation to Mars missions (NASA 1992) and made imperative by the recent announcement of the discovery of cellular lifeform fossils in Martian meteorites.

Quarantine implications exist for all transfers of material between bodies in the solar system, such as the return to Earth of cometary samples, for missions like Rosetta, and for probes destined to land on satellites, a worrying case being Europa where liquid water and exotic lifeforms may exist under its icy surface.

In all of the areas of concern here identified, as in other areas that may emerge, it is essential to recognise the scientific and engineering tradeoffs. A project designed to provide great scientific returns in one field may cause problems to other fields of study. In fact, there are two distinct classes of pollution: one due to engineering constraints in operating an interplanetary mission (propellant residues, biocontamination from limited sterilisation) and the other class intrinsic to the scientific study itself (debris from impacting a small body to reveal its structure, atmospheric

perturbation due to reentry effects, etc). In either case, it is essential that the scientific goal justify the perturbation.
Pollution must be minimised consistent with engineering and cost constraints in the former case, whereas for the latter it must be weighed against the scientific goals of the mission. In all cases, the challenge to mission planners is to devise procedures which will at the very least minimise pollution outcomes.

This brings us to the circularity problem. Satisfying the above requirements requires sound knowledge of conditions at the target body, which is the object of the mission in the first place. It is therefore vitally important that space exploration should continue on a steadily evolving pattern, gathering essential data upon which sensible anti-pollution measures may be based later when they are needed.

PRELIMINARY INVESTIGATIONS REQUIRED

In general terms, total prevention of interplanetary pollution of any kind is neither achievable nor desirable in the strict sense. The unavoidable artefacts from the Apollo landings have polluted the lunar environment but the gains from those missions justified the minor loss of pristine conditions. The same with the proposed manned Mars missions. Any scientifically acceptable policy on pollution, therefore, must permit a balance between immediate scientific gain and future scientific loss. To achieve this balance sensible preliminary activities must be undertaken, as follows:

1. **Identify likely sources of undesirable pollution.** This has been commenced by the Working Group, as outlined above, but undoubtedly new sources will emerge in the future.

2. **Measure current levels and predict future levels.** To avoid the circularity problem, initial measures should be assessed as far as possible by remote sensing techniques. Extrapolation to future conditions is often difficult, but necessary for the next phase.

3. **Assess future impact of pollution on research.** This, of course, depends entirely on the research goal(s). It is here that the expectations of researchers need to be promulgated and used to define allowable pollution limits for the goal(s) to be met. This will require comprehensive study with independent verification of the likely outcomes.

4. **Investigate likely severity and irreversibility.** Potential sources of pollution may range from innocuous to severe, and the effects may range from short-lived to permanent, calling for the exercise of careful judgement in setting allowable limits.

5. **Formulate preventative or minimisation procedures.** This is an evolving process. Total pollution prevention may well be impossible. However a cautious approach must be adopted at first and only relaxed when allowable limits become known.

6. **Set guidelines for assessing preservation values.** These call for reliable knowledge of the primal state, which brings us back to the circularity problem. This also demands a cautious approach, since it is safer to relax constraints than impose them under or following what may be an irreversible change of state. At the same time it must be acknowledged that it is hardly necessary to preserve the pristine condition of every minor body in the solar system. This provides an escape from the circularity problem.

7. **Develop means to protect sensitive environments.** Terrestrial experience suggests that this is often more feasible than at first feared. The challenge of environmental protection is far easier

to meet when sensible research studies have been carried out and applied before the problem becomes intractable.

8. **Seek ways to increase awareness of the issues.** The secret of success in preventing interplanetary pollution must surely lie in making all stakeholders fully aware of the issues.

FUTURE DIRECTIONS

At the present epoch the degree of man-made pollution in interplanetary space is negligible. This gives no grounds for complacency, however. The problems now evident in cislunar space (Simpson 1994) are the result of failure to recognise adequately the potential for harm of totally unconstrained and unmoderated projects.

It is not the intention of the Working Group to advocate the imposition of restrictive laws and non-compliance penalties. Rather it is the desire to flag the problem areas and rely on the power of persuasion which can be exercised quite effectively in an open society.

Of course it will become necessary to establish some kind of organisational structure, if only to ensure effective communication between all parties and act as arbiter of conflicting expectations. The report of the initial Working Group suggested that this should function at two levels: an international council, with representation from all nations engaged in deep-space exploration, charged with the responsibility to assess all forms of pollution, develop appropriate recommendations, and continuously monitor the situation; and an expert advisory panel to provide the necessary scientific and technical advice to the council.

If the above structure is implemented wisely, so that it functions effectively, the scope for ad hoc protest groups will be greatly curtailed. Otherwise they will emerge to plague legitimate space missions and in the long run cost space budgets far more in defensive measures and appeasement than the cost of sensible pollution minimisation measures. That is the choice, and for how much longer the choice will be available depends on the foresight shown over the next few years.

ACKNOWLEDGMENT

As well as input from the earlier report mentioned above, incorporating D. Crawford's suggestions for preliminary investigations, very valuable comments have been received from A. Harris and M. Ahearn and included herein.

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II. EFFECT OF POLLUTION ON PLANETARY SATELLITES

(L. Ksanfomality, Commission 16)

During the last few years of space research the role of a detailed study of the origin and evolution of planetary satellite has become one of most important and informative branches of space science.

Recent advances in the subject have flowed from the accumulation of an invaluable body of information based on a growing understanding of the revealing records carried by the solid surfaces of minor bodies of the Solar system. Currently in development are new methods of investigating under-surface layers and the deep internal structure of Earth-type planets. Despite serious efforts, our understanding of giant planets, that is to say the physics of liquid/gas high pressure regimes, is well behind our understanding of Earth-type planets. As for records of early history events around giant planets, only their satellites are of any use.

The physics of celestial bodies posessing a solid surface are to a large extent based on the study of satellites, because they are much more numerous than the four terrestrial-type planets. Natural satellites display a large variety of catastrophic features, ranging from large meteoritic craters all the way up to the reformation of satellites fully destroyed by a collisiona episode (as in the case of the Uranian satellite, Miranda). Furthermore, some Jovian satellites may have the deepest oceans in the Solar system (Europa, and maybe Ganymede), a prospect suggesting new kinds of fundamental investigations in the future.

The majority of satellites of the Solar system planets have their surfaces directly exposed to effects of pollution, without the buffering action of atmosphere. In fact, this type of pollution is the most widespread in the Solar system, since of all sixty known satellites of Solar system planets there are only two posessing an atmosphere - Triton and Titan. Triton's atmosphere is quite tenuous and may be neglected from the standpoint of possible artificial pollution. Only the case of Titan is a special one for our consideration. Element species produced by a probe's motors do not change the atmosphere significantly, except in the case of a nuclear explosion.

That is why the major concern is pollution produced by rocket and probe propellants and residues of nuclear explosives and generators to planetary satellite surfaces, of icy nature, regolith, or mixed. Solely regolith surfaces are typical of satellites of Earth, Mars, some of Jupiter, and asteroids. Mixed ice/regolith (in varying proportion) represents the nature of the surfaces of other satellites of Jupiter, Saturn, Uranus, Neptune and the Pluto/Charon pair.

The surface of satellites is a unique source of our knowledge about the early stage of the Solar System, its evolution and of the role and intensity of meteoritic bombardment throughout its history. Regolith composition reflects processes of separation in the primordial dust/gas nebula, and delineates later migration of the material in the Solar system. The huge events with traces like Walgalla (Callisto) or the Caloris Basin (Mercury) are test sites for new theories such as the effect of focused shock waves penetrating through the whole celestial body. Sometimes the regolith composition permits us to determine the extent of matter exchange between distant celestial bodies, for example SNC-meteorites. Thickness of a regolith layer, its structure, surface morphology (e.g. grooves, craters, cracks), all carry significant information about processes of regolith' reworking and surface formation.

Radionuclide analysis provides very important clues about the age of the regolith material. All of this information may be masked and lost in the case of a nearby nuclear explosion. The surface affected by the explosion will be of no use for attaining the goals listed above. Moreover, debris thrown out in all directions may reach and contaminate the surface of other celestial bodies. Then when they are studied and tested they will provide false data. Age and history and even structural information would be destroyed forever.

One of the most delicate and precise techniques for measuring the nature of regolith and atmosphere constituents is isotopic composition analysis which of course is distorted by a nuclear explosion. Subsequently this powerful method is to a large extent useless. Even in the event of a non-nuclear (conventional) explosion, or exposure to the exhaust of probe motors, a degree of local pollution is inevitable and analysis results are compromised.

It is not suggested that there should be a halt to active investigations of the planetary satellites. However, taking into account all items mentioned above, such missions should be accurately and carefully planned. For the sake of future exploration, vulnerable areas and satellites must be identified as soon as possible by means that should be agreed upon by the scientific community. It will help to avoid errors in conducting the exploration of the Solar system and protect the interests of the scientists coming next. The IAU should consider establishing a special databank where all information concerning pollutable areas (noting the type and scale of pollution) of any celestial body may be documented.

III. SPACE DEBRIS FROM UNDESIRABLE TRANSFER OF SURFACE MATERIAL AND OTHER POORLY CONTROLLED OPERATIONS (M. Yoshikawa, Commission 20)

One aspect of the interplanetary pollution problem that is likely to arise in future is the indiscriminate disposal of small objects such as the natural material from solar system bodies (asteroids, comets, moon, and other satellites, etc.) as well as some artificial materials from space vehicle and space station operations. We will face such problems, for example, when we boost the surface material of the Moon to a Lagrangian stability zone and there use the material for various purposes such as constructing space habitats or factories. Similar problems will be encountered when we begin to use asteroids as a source of raw materials. Before such activities are started, it is essential to know the required accuracy to control such mass transfers and we must investigate what will happen to any material that escapes adequate control, also the full extent of the damage or danger it may present.

1. **From space debris around the Earth to interplanetary space debris.** At present, a great many man-made objects are orbiting around the Earth. Some of them are operational satellites but most of them are undesirable objects, such as defunct satellites, broken pieces of satellites or rockets, and small particles of paint or chemical materials. More than 7,000 objects larger than 10 cm has been detected and their orbits are well determined. However the number of smaller objects is much greater and it is estimated that there are more than 3,500,000 objects larger than 0.1 cm and the total mass is 3,000,000 kg. Such fragments of orbital debris are very harmful for the utilization of space. They can destroy functioning satellites by collision, and if they collide with manned space stations the damage could be fatal. In fact, we have already observed numerous small impact craters or pits on exposed surfaces of artificial satellites and space shuttles.

   The present situation of space debris is therefore serious and in recent years we have been carrying out many studies to solve the problems caused by space debris (Simpson, 1994). In a sense, however, it is too late to clean up the space around the Earth. We can try not to make new space debris, but it is quite difficult to return to the ground what is already there. The most practical ways to avoid collisional damage is to navigate spacecraft to avoid encounters with large debris and to equip them with adequate shields to prevent damage by collisions with smaller fragments.

   While the problem of space debris around the Earth is now very important and serious, interplanetary space by contrast remains almost free from man-made debris. However, the number of missions in deep space is steadily increasing, so we should start to consider interplanetary space debris as a potential future problem. Since we have now experienced the harmful nature of space debris around the Earth, we should not repeat the same mistakes in the interplanetary space.

2. **1991VG, the first interplanetary space debris ?** In 1991, a single small object was found, which approached the Earth at a closest distance of 460,000 km. It was called 1991 VG (MPC 20823). The orbital elements of this object are semimajor axis = 1.027 (AU), eccentricity = 0.049, and inclination = 1.4 (degs), so its orbit is quite similar to the orbit of the Earth. Moreover, orbital calculation shows that 1991 VG encounters with the Earth every 17 or 18 years, and the relative velocity at the encounter is low as 3 km/s. For near-Earth asteroids, the typical relative velocity at the encounter with the Earth is 8 km/s or much larger. Therefore, it is said that 1991VG is not a natural asteroids but an artificial spacecraft which was launched in the middle of 1970's. If this proves to be true, 1991VG is the first man-made interplanetary space debris that has ever been detected.

We can also know from orbital calculation of 1991 VG that it was moving between 0.98 AU to 1.1 AU from the sun before the encounter in 1991, and after the encounter its parameters changed a little. The orbital elements of 1991 VG may have rather large errors because the period of observation was not very long. Therefore, it is difficult to calculate its orbital evolution precisely. But, at least we can say that this object may encounter the Earth many times from now on, resulting in large changes to its orbit. Indeed, if we continue to calculate the orbital evolution of 1991 VG for the next 500 years, we find that its semimajor axis changes randomly between 1.0 AU and 1.06 AU by close encounters with the Earth.

Fortunately, we do not have many items of man-made interplanetary space debris at present. However, the number of spacecraft that are likely to be launched will increase from now on, so the amount of interplanetary space debris is also likely to increase. The total amount of interplanetary debris could rise to an unacceptable degree if we start to boost into orbit the surface materials of solar system bodies with low escape velocities for use in space construction projects. In such cases, we may finish up with a broad spectrum of debris embracing the equipment employed as well as the mined source body. It is not unlikely that such a mixture of artificial and natural space debris may lead to significant problems for future scientific research.

3. **Orbital evolution of small bodies in the inner solar system.** As the case of 1991 VG shows, the orbital evolution of small bodies in the inner solar system is basically chaotic. This is because small bodies suffer a lot of close encounters with inner planets, that is, Mercury, Venus, Earth, and Mars (Yoshikawa, 1994). So the orbits of near earth asteroids frequently change and usually do not remain in a fixed orbit (Milani et al. 1989).

Therefore, the essential difference between the debris around the Earth and debris in interplanetary space is the variability of their orbits. In the case of space debris around the earth, the orbital elements, especially the semimajor axis, do not change much when the effect of air drag is negligible. On the contrary, in the case of interplanetary debris, orbits are much more likely to change, principally by close encounters with planets. This means that once a shower of debris is released into interplanetary space, the fragments will disperse over a wide area, which in turn means that a large fraction of the solar system may become polluted by it.

4. **Problems to be solved before utilising interplanetary space.** In order not to repeat the same problems as we have in cislunar space it is vital that careful consideration should be given well in advance to adequately control space debris. The main avenues of investigation are as follows:

(1) Thorough analysis of the future orbital evolution of artificial objects and mined material launched into interplanetary space.

(2) Analysis of required accuracy to control mass transfers.

(3) Development of technology for transport of materials with high precision.

(4) Development of effective methods for retrieving misdirected objects.

The essential intent is to eliminate the avoidable pollution of interplanetary space. Without adequate prior investigations of the above matters it seems certain, from past experience, that lack of sufficient foresight will inevitably lead to degradation of the interplanetary environment. This undesirable outcome must be prevented if at all possible.

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IV. LIGHT POLLUTION IN THE INNER SOLAR SYSTEM

(B.A.S. Gustafson, Commission 21)

Since all-sky maps of the infrared sky were made by the IRAS (Infrared Astronomical Satellite) and COBE (Cosmic Background Explorer), much effort has been spent on characterizing the broad scale interplanetary infrared emission to extract and map the brightness distribution in the universe. Identification of the interplanetary component has been based primarily upon the apparent annual variation of brightness as the Earth orbits the Sun (Hauser, 1996). The infrared signal due to a disrupted km-size near-Earth object (comet or asteroid) will differ from the zodiacal cloud in spatial extent and could easily exceed that of the zodiacal emission. The result is a serious complication to any future effort to observe deep space and this impact should be considered beforehand.

Studies of the zodiacal light and infrared emission, the only source of broad scale information about the meteoritic complex, would also be affected. Rather than the dominance of a single source, there is mounting evidence for the heterogeneity of the zodiacal cloud. The IRAS data contain trails of dust that are clearly cometary (Sykes, 1990) and bands that are from asteroid families (Dermott et al., 1996a). Levasseur-Regourd (1996) shows that the physical properties of the dust varies with heliocentric distance and orbital inclination and that the emission deviates from that of a blackbody. We have only started to understand these sources and unravel some of the components and this may lead to renewed observational efforts including the visible part of the spectrum. Debris from a disrupted asteroid would not necessarily preclude these efforts. It could even be argued that study of a breakup and evolution of the dust distribution could serve as a test of theoretical modeling. However, the impact of such an experiment requires careful study.

To illustrate the broad scope of zodiacal light studies, we notice that Dermott et al. (1996b), could show that the Sun is displaced from the center of the cloud as observed by IRAS and that resonances led to an accumulation of dust just outside the Earth's orbit which is also seen in IRAS

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V. POSSIBLE EFFECTS OF HUMANKIND'S ACTIVITIES IN SPACE UPON THE FLUX OF METEOROIDS AND INTERPLANETARY DUST IN NEAR-EARTH SPACE AND INTO THE ATMOSPHERE.

(D. Steel & Z. Ceplecha, Commission 22 & A. Harris, Commission 15)

The total mass of small meteoroids and interplanetary dust in the inner solar system is quite small, being equivalent to just a few cubic kilometres of rock. Thus the total fragmentation of an asteroid or comet a few kilometres in size could cause an increase in the spatial density of such smaller particles by a factor of several times. This could have a number of important consequences for us, of which we will briefly describe a few:

1. Presently about 40% of all the light in the night sky at the time of New Moon (when observing time on large telescopes is most valuable) is due to the scattering of sunlight by interplanetary dust particles in the 10-100 micron size range. Any enhancement in the dust population would clearly have a detrimental effect on both ground- and space-based astronomical observations.

2. Small dust particles which do not ablate but remain intact upon atmospheric entry have residence times of months to years. These cause scattering of light, from whatever source, and thus both increase the opacity of the atmosphere and also cause diffuse scatter which can limit some types of astronomical observation. Terrestrial sources of dust (such as major volcanic eruptions) clearly have a larger mass input to the atmosphere than such extraterrestrial sources, but with differing spatial characteristics (both in terms of geographical locations and vertical profile), different light scattering properties, and longer residence times. A comparison between the deleterious effects upon ground-based astronomical observations is therefore difficult.

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The total mass of small meteoroids and interplanetary dust in the inner solar system is quite small, being equivalent to just a few cubic kilometres of rock. Thus the total fragmentation of an asteroid or comet a few kilometres in size could cause an increase in the spatial density of such smaller particles by a factor of several times. This could have a number of important consequences for us, of which we will briefly describe a few:

1. Presently about 40% of all the light in the night sky at the time of New Moon (when observing time on large telescopes is most valuable) is due to the scattering of sunlight by interplanetary dust particles in the 10-100 micron size range. Any enhancement in the dust population would clearly have a detrimental effect on both ground- and space-based astronomical observations.

2. Small dust particles which do not ablate but remain intact upon atmospheric entry have residence times of months to years. These cause scattering of light, from whatever source, and thus both increase the opacity of the atmosphere and also cause diffuse scatter which can limit some types of astronomical observation. Terrestrial sources of dust (such as major volcanic eruptions) clearly have a larger mass input to the atmosphere than such extraterrestrial sources, but with differing spatial characteristics (both in terms of geographical locations and vertical profile), different light scattering properties, and longer residence times. A comparison between the deleterious effects upon ground-based astronomical observations is therefore difficult.

3. To some extent the aeronomy of the upper atmosphere is affected by the influx of meteoroids and dust (currently about 40,000 tons/year: Love and Brownlee, 1993), so that the terrestrial environment could be altered if that influx were enhanced.

4. Although small inputs of dust are unlikely to severely attentuate the amount of sunlight reaching the ground, larger inputs could have a very significant effect. The debate over the anthropomorphic greenhouse effect is concerned with supposed eventual global temperature increases of a few degrees at most; as a rule-of-thumb, an increase in the dust content of the upper atmosphere such that an additional one percent of the solar flux is reflected away will result in a cooling of the Earth by a substantial fraction of a degree Celsius. Whilst episodic dusting by infrequent meteor storms (or by dust injections from massive volcanic eruptions) have effects which last for a year or two, and thus no great long-term effect due to the heat capacity of the oceans, the production of a high-density meteoroid stream in the aftermath of a deliberate asteroid or comet nucleus disruption could result in an annual meteor storm and therefore a repeated replenishment of the atmospheric dust content on a time-scale shorter than the fall-out time. This would lead to a consistent cooling of the planet over a time period defined by the lifetime of the meteoroid stream (millennia at least) and the length of time that it takes for precession to carry the node away from 1 AU.

5. Satellites in geocentric orbit suffer impacts by small natural particles in excess of the impact rate by man-made space debris, and these are a significant cause of abrasion and damage to functioning satellites. Any increase in the interplanetary flux would make this problem worse. It has already been realized that satellites in orbit face a marked increase in the impact hazard in 1998-2000, due to the advent of the Leonid meteor storms (Beech et al., 1995); the creation of artificial meteor storms through the disruption of any comet or asteroid passing close by the Earth could exacerbate this problem, with very serious economic consequences quite apart from the problems of a loss of communications facilities which are now taken for granted by civilization.

6. The breaking up of, say, a one kilometre asteroid into some thousands of fragments 50-100 metres in size would be an event with long-term consequences, if these had a node at 1 AU: the monolithic parent would be quite easy to track and then divert as required, whereas the fragments would pose a possibly-insuperable tracking problem, and might hit the Earth from time to time causing atmospheric detonations in the 10-100 megatonne range. We emphasise that the short-term dust problem, as pointed out earlier, could be of just as much concern in such a scenario.

For all of the above reasons, and others, we should be cautious about any proposed spacecraft experiment that might disrupt an asteroid or comet, especially until we have a better understanding of their strengths and compositions. Various missions have been proposed that would involve probes striking either asteroids or comets at hypervelocity, for exploration purposes. For example the U.S. Department of Defence's planned Clementine 2 spaceprobe would involve three 10 kg projectiles being delivered at speeds above 10 km/sec into three near-Earth asteroids, whilst a project proposed in the NASA Discovery class series would aim to break apart a cometary nucleus in order to investigate its interior composition and structure.

In addition, there have been various discussions of how an asteroid or comet on a collision course with the Earth might be diverted (Ahrens and Harris, 1992; Canavan et al., 1993; Melosh and Nemchinov, 1993; Gehrels, 1994; Willoughby et al., 1994; Ivashkin and Smirnov, 1995). One might note that the fragmentation of any object with an orbit having a node near 1 AU (which clearly any potential Earth-impactor must have) would lead to a more immediate increase in the terrestrial influx of material than would the disruption of any object with, say, perihelion at 1.3 AU, or aphelion at 0.9 AU. If experiments designed to improve our understanding of how we might divert an Earth-threatening object are to be carried out, then preferable targets, for the above reasons, would be asteroids with aphelia within 1 AU (none are yet known, but presumably they do exist since several Atens have aphelia close to the Earth's orbit), and comets with perihelia well beyond our orbit (perihelion distance greater than 1.3 AU, say) since sub-terrestrial comets are not to be expected. Over the time-scale appropriate for the orbits of small bodies to evolve such that Earth-impacts are possible, the debris produced by such broken-up comets would be expected to be so well dispersed that there is no marked enhancement of the annual terrestrial influx. We suggest that it would be prudent to wait and see the outcome of limited experiments such as Clementine II before any mission is attempted that could create a significant amount of debris.

In discussing all of the above, we note that in the solar system asteroid and comet disruptions occur naturally. Cometary decay occurs, apparently, in two main modes. The first is the normal production of small meteoroids (the majority of the mass is in the millimetre to centimetre range), these being carried away from the nucleus by gas pressure. The second is when a cometary nucleus splits into two or more fragments, this occurring with some regularity; cometary splitting is observed every year or two on average, with individual nuclei splitting perhaps once every ten to fifty orbits on average. Such splitting can result in the instantaneous release of large amounts of gas, dust and small meteoroids (so that some comets are discovered soon after a splitting due to their sudden brightening; an example is P/Machholz 2 - see Asher and Steel, 1996). If asteroids are indeed composed of one or more large bodies, then their disruption due to tidal forces or large meteoroid impacts will be expected to result in a limited number of large fragments being produced, and a restricted amount of smaller debris (dust and small meteoroids). Such events are not thought to occur frequently in the inner solar system, although they clearly do happen in the main belt.

We have briefly described the natural processes leading to the break-up of asteroids and comets so as to be able to contrast such events with those which might occur should one or more such bodies be artificially disrupted. Meteoroid streams are produced by the gradual release of many small particles by comets, whilst cometary splitting produces a sudden increase in the release of small meteoroids plus two or more very large fragments. If a cometary nucleus were deliberately disrupted using a nuclear weapon, say, the result might well be that the mass of the daughter products is held mostly in fragments between 1 and 100 metres in size; the consequences of such an event might be quite different from any naturally-occurring fragmentation. A similar effect might be produced by the impact of a substantial kinetic energy projectile on a comet or asteroid, and this might be argued to be similar to naturally-occurring large meteoroid/small asteroid ("boulder") impacts upon larger bodies. In the inner solar system, however, the population of boulders is believed to be too small to lead to an expectation that such events occur naturally with any great frequency, with only circumstantial evidence existing for comet break-up through such mechanisms (e.g., Babadzhanov et al., 1991). Asteroid families exist in the main belt due to inter-asteroid collisions (Zappala and Cellino, 1994), and laboratory hyper-velocity impact studies, and astronomical observations, lead to an expectation of most of the mass of the daughter products being held in moderate to large-sized fragments, and not dust or small meteoroids. Asteroids, with an internal strength which might be presumed to be substantial, might therefore be expected to fragment into a limited number of sizeable bodies. Comets might do likewise, although the fragments produced would have 50 percent or more of their surfaces being freshly-exposed volatile material, leading to the onset of greatly-enhanced volatile sublimation, release of small meteoroids, and subsequent "natural" fragmentation. On the other hand, we do not yet know enough about cometary nuclei to be sure that they are not so fragile that total nucleus disintegration of the nucleus might occur immediately upon being dealt a severe blow by some artificial means. The above does not imply that near-Earth asteroids may be probed roughly, comets needing greater care: it is believed that a substantial fraction of near-Earth asteroids are actually extinct or dormant cometary nuclei, so that there is a chance that delivering a relatively small projectile into such an object could result in the fracture of an insulating crust of silicates and heavy organics, provoking a resumption of cometary activity. At this stage in our investigation of the small bodies in the solar system, our recommendation must be that they are all "handled with care."

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