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The Role of Comets and Asteroids in Solar System Development: Space Exploration [and Discussion]

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The role of comets and asteroids in Solar System development: space exploration

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Exploration by space missions of the near-nucleus regions of comets Halley and Grigg–Skjellerup has resulted in valuable but expensive snapshots of cometary phenomena. The ‘ground truth’ from such missions, which can be established only by this means of dedicated space exploration, provides essential inputs to models of cometary processes. It also gives calibration data for a very wide base of cometary and asteroidal observations, past, present and future. Seen as objects which are both eroded by impacts from interplanetary dust and also the progenitors of interplanetary dust, we find both asteroids and comets are needed to contribute to this population. Contrary to expectations, as new data on the asteroids and comets is analysed, we find the differences between the two classes of primordial body is very much less distinct; accounting for the interplanetary distribution and properties of dust mass requires not only both classes of object but also a distribution of mixed classes.

ESA’s newly selected cometary mission Rosetta will offer a unique opportunity, during a rendezvous encounter from aphelion to perihelion, for the extended and detailed *in situ* observations of a target comet. It will also act as a valuable focus on the nature and role of comets in both the origin and development of the Solar System.

1. Minor bodies and the terrestrial context

The planets may be viewed as the end-point of accretionary processes acting on the residues of matter surrounding the core of the pre-solar nebula; even now, though, they cannot be divorced from a continued interaction with the smaller – perhaps less ‘successful’ – proto-planets and fragments which are still abundant. The thrust of this review is to identify current progress towards characterizing this ongoing collisional scenario. We see two main progenitors of this process and the source of dust particulates – the asteroids and comets. These two object classes have generally been distinguished by two factors:

(i) comets (‘hairy stars’) have a tail or coma thus exhibiting a significant atmosphere, sustainable by volatile release, and

(ii) comets have been resident in, though not necessarily formed in, the outer Solar System for a time-scale comparable with the formation of the Solar System.

Very much the thrust of modern planetary exploration is the characterization of new bodies – the discovery of new satellites of known planets and, especially, their topology which extends the historical time-base of their surface exposure

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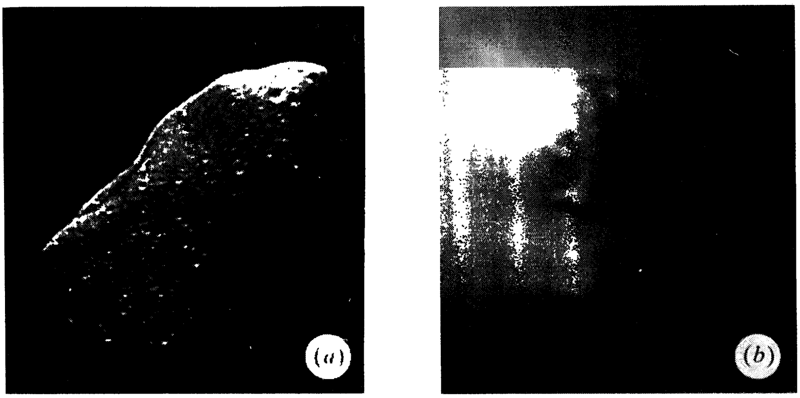

Figure 1. (*a*) Spacecraft Galileo's first glimpse of asteroid Gaspra. At small dimensions crater overlapping leads to the development of a regolith despite weak gravitational forces (photo courtesy M. Belton). (*b*) Comet Halley's nucleus near to perihelion, imaged by the Halley multi-colour camera (photo courtesy H. Keller (Keller *et al.* 1986)). Craters are the result of active spots, past or present.

as a record of the interplanetary environment. The successful fly-by of asteroids Gaspra and Toutatis (Belton *et al.* 1992) has provided data on the impact environment (from smaller asteroids and meteoroids) showing the development of a regolith akin to the moon, figure 1*a*. The fly-by of comet Halley, and spectacular imaging of the nucleus by the multi-colour camera (figure 1*b*), revealed a not dissimilar figure but created more by the evaporational insolation of ices (Keller *et al.* 1987). We see these bodies not only as a host for erosion from lesser bodies in space, but also as the driving force for impact damage on other bodies. Asteroids and comets generate fragments which impact other bodies; asteroids, themselves, are of course generally the result of an impact fragmentation of a larger body. Especially within families such as the Hirayama asteroids, they form a population in collisional equilibrium extending down to the generation of micron grains. The relative scarcity of comets and the surface evaporation rate renders comet–comet and indeed comet–meteoroid impacts to be of minor importance, but the meteoroids liberated are competitive with asteroidal grinding in populating an impact erosion environment. Current studies are aimed at understanding the relative contributions from asteroids and comets.

Study of proto-planetary surfaces and the role of small bodies requires a wide range of parameter space, namely:

(i) time-scales: from current impact rates to the study of planetary surface features over geological ages – typically 200 million years;

(ii) dimensions: from submicron grains to the impactors capable of causing the near-catastrophic lunar maria;

(iii) techniques: from laboratory micro-analysis to remote sensing; from space-borne detectors to lunar quakes and near-Earth asteroid surveys.

The influx of matter on to planetary surfaces has to be assessed on an historical and present basis. The extension to historical epochs results in two implications: (1) the extension of an upper limit of integration to larger masses and (2) the question of flux variations and episodic changes. At even earlier times, we may enter the latter stages of the planetary accretion process – and certainly the late stage bombardment, some 3×10^9 years ago. The size of an impactor also determines its transmission through a planetary atmosphere – if at all. If we require an influx to a planet of volatiles, e.g. to the terrestrial crust, then impactors of the kilometre scale are required to deliver their cargo of ices. At the extremely small range of the dimensions though, micro-meteorites *can* successfully penetrate, many without ablation; yet their contribution will be depleted in water and other light volatiles by virtue of atmospheric entry and their recent and fairly short sojourn at elevated temperatures in the inner Solar System. Nevertheless, they can inject significant rare earth elements such as iridium and osmium, readily analysed (Love & Brownlee 1993) in ocean sediments along with the ablation products from meteoroids, rich in iron, manganese and (but less conspicuous) silicates. Assessment of the small particle influx and balance in the Earth's crust depends on space measurements; such data, though now well defined as an impact rate, has been open to a duality regarding interpretation. In addition to this astrophysical question of the distinction between asteroids and comets, we now have an additional factor entering the space age assessment of these natural fluxes: space debris.

2. Space missions to the minor bodies

(*a*) *Asteroids*

Fly-bys by the NASA spacecraft Galileo of two asteroids, Gaspra and Toutatis, have returned the first high-resolution imaging. Information on the impact crater size distribution is used, in a manner similar to the lunar surface, to assess surface exposure ages. The large craters within the overall size distribution, which are nevertheless smaller than the catastrophic impact limit, are in a state of production and show a higher size index; below a critical crater dimension, of some 10–100 km, the distribution has lower size index where equilibrium is established. By such crater overlapping, a significant gardening process generates a regolith. This critically affects the optical and thermal properties which we observe through more remote sensing. Before such *in situ* sensing, regoliths were generally considered as matters for speculation.

Because many asteroids are in collisional equilibrium and relative motions are chaotic, their topology may reflect a confused record. At very much smaller dimensions, and within 1 AU heliocentric distance, we see collisional balance, and especially catastrophic rupture of millimetre grains as the source of micron-sized particles which are then expelled from the Solar System; these β particles were first detected by spacecraft as a flux from solar directions (Berg & Grün 1973). Asteroid comminution products, during their orbital decay towards the Sun under Poynting–Robertson drag, may also be detected impacting the Earth, along with cometary fragments. New data on this role is discussed in § 4.

(*b*) *Comet missions*

Three cometary encounters have been effected: Giacobini–Zinner (ICE spacecraft in 1985), Halley (Vegas 1 and 2, Suisei and Sagigake and Giotto, 1986) and Grigg–Skjellerup (Giotto, 1992). Results, spread through some thousands of scientific papers, highlight the *in situ* study of comets as a phenomenon where 'astrophysical phenomena' can be experienced and understood; where, for example, the disciplines of plasma studies, dust and biochemistry must actively interact.

Measurements of the chemical nature of grains by the Vega and Giotto dust particle impact mass analysers (PIA) (Kissel *et al.* 1986) showed varied composition. Silicate grains, perhaps, for example, pyroxenes, olivines and organic grains like CHON were seen as either distinct particles but also of mixed composition. Although *in situ* microscopy must await Rosetta's cometary rendezvous, we can perhaps look with some anticipation at the interplanetary dust particles (IDPs) characterized by Brownlee. The space heritage of some grains was first demonstrated by their helium enrichment (Rajan *et al.* 1977) and indeed certainly the overall characteristics of the porous chondritic aggregates fits well into the cometary source we have long suspected. We see that the size distribution, and especially the *mixing* of discrete grains of different minerals, extends down to below the micron region. We can then perhaps now understand the data from the comet Halley particle impact analyser experiment on Giotto and the PUMA data on Vega which, even in its detection of grains as small as a micron, must nevertheless have been yielding in many cases an average composition of the comet bulk.

We can also study these cometary grains with the help of spectral measurements of comets. Recent comparative studies of the emission characteristics of comets by Hanner *et al.* (1993) have compared them with interplanetary dust particle spectra. Three comets (Halley, Bradfield 24 and Levy 29) have near identical spectra; the authors ask how the silicate features can be related to IDP spectra. IDP spectra fall into quite different classes, but none fit these comets – we need a *mixture* of IDP grains to synthesize a comet. Further, these cometary spectra call for the crystalline silicate grains to have been processed – perhaps made glassy in the solar nebula by mild melting before aggregation.

Our current view of a comet as a repository of pristine pre-solar matter may have to be modified somewhat, to accept that:

(i) a particular comet is likely to contain different grains mixed at the smallest scale and will include further grains of mixed origin, and

(ii) cometary grains may have been partly processed in the solar nebula before aggregation, and

(iii) cometary grains within one comet are likely to comprise samples from different parts of the pre-solar nebula.

We cannot avoid, then, a closer tie between comets (which were commonly thought to be 'very pristine') and asteroids which were always admitted to be 'less pristine'! Though asteroids have been processed much more extensively it is becoming more likely that cometary grains clearly may not escape entirely this pre-aggregation thermal processing – it is merely a matter of degree. This distinction may therefore be determined only by the heliocentric distance of aggregation.

The size distribution has been measured on both Vega 1 and 2 (Mazets *et al.* 1987; Vaisberg *et al.* 1987), on Giotto (McDonnell *et al.* 1987) for comet Halley, and on Giotto-GEM for Grigg–Skjellerup (McDonnell *et al.* 1992). Although the Vega measurements define better the structural variations in the dust concentration and size distribution, the close encounter distance of the Giotto spacecraft provided the area–time product of detectors to extend to particles in the centimetre region. It is in that size region where the mass index decreased significantly; at smaller dimensions the size distribution mimicked that of the interplanetary dust population. This decrease of the index means a heavy concentration of mass in the centimetre region – more than in the whole region integrated below a milligram. Even in terms of particle area, the larger particulates are seen to contribute a comparable area. Two results of significance are seen from the *in situ* measurement, namely:

(i) the dust-to-gas ratio cannot be inferred from micron dimensional grain spectra alone; the contribution from the (perhaps unseen) larger grains may dominate, and

(ii) the emission and reflection spectra of cometary dust will be a balance between small (*ca.* 10^{-5} m) and large (*ca.* 10^{-3} m) grains, dependent on the 'true' gas-to-dust ratio rather than their generally lower value seen by visual or near infra-red remote sensing.

After modelling of expulsion velocities is used to transform back to the body of the nucleus, the Halley data, derived from expelled grain fragments up to 1 cm, shows a dust-to-gas ratio of 2:1. This may set the scene for Rosetta's encounter with the comet target Schwassman Wachman III, but the ratio cannot be universal in the cometary population – it would be counter to our concepts of their formation. In the exploration of the second (of only two comets) by dedicated space missions, however, the DIDSY dust detector on Giotto (McDonnell *et al.* 1987) found a similar large mass excess; in fact the cumulative mass index was even lower ($\alpha = 0.45$) for Grigg–Skjellerup. Supported by IRAS data and radar data on other comets identifying the trails of centimetre-scale meteoroids in the orbit (Sykes 1993), it seems as if the integrated meteoroid mass could well dominate the total mass content of comets. Rather more than 'dirty ice', comets might be better envisaged as 'frozen soil'. More recently we see the vital need to balance the cometary population with the contribution from asteroids to assess the total particulate environment and, especially, the planetary and terrestrial impact environment. Acquiring the information and achieving the modelling to account for such mass budgets is, however, formidable.

3. Recent space measurements

(*a*) *Impact measurements in Earth orbit data*

Our definition of the influx of interplanetary matter upon the Earth, and especially the relative contribution from asteroids and comets, is not a clear one yet. In terms of the size distribution of the total component and directionality, we look to NASA's long diffusion exposure facility (LDEF) as the 'gold standard'; with an area of 110 m^2 and an exposure time of 5.75 years this gives a very meaningful assessment of the space environment from particles up to a millimetre in diameter. Though largely passive, its detectors provide impact cratering and perforation data from the submicron β particles detected in deep space to the radar meteoroids. The calibration overlap with this radar data, where the velocity and radiants are available, will prove critical to interpretation of space data and the calibration of radar data.

The flux distribution from impact data on LDEF for five directions is shown in figure 2. We see, primarily due to the orbital velocity which leads to enhanced sensitivities and increased flux, a much higher flux in the ram (east) direction. The east, north and south faces of LDEF are readily accessible by space debris, which may be considered a contaminant in purely astrophysical terms. Space debris cannot readily access the space or Earth faces and its approach velocity would,

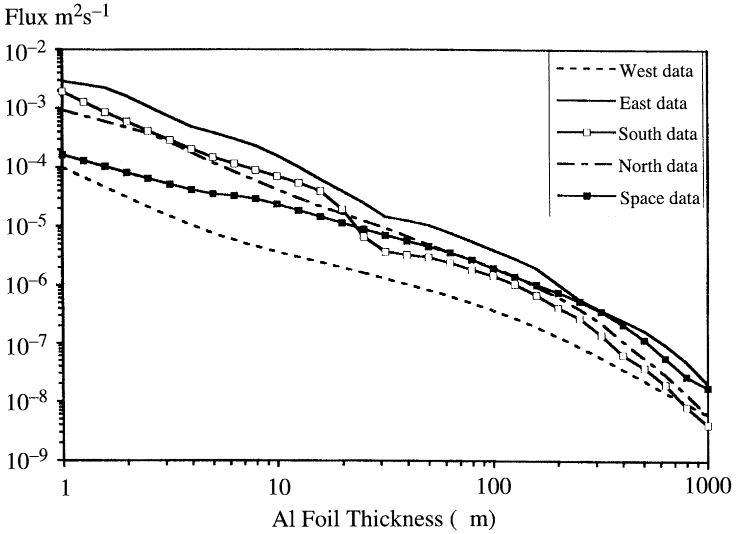

Figure 2. Impact penetration fluxes measured on NASA's long duration exposure facility (LDEF) in the major directions relative to the orbital vector. The small-scale variations are not consistent with an isotropic and constant flux.

in any case, cause much diminished impact features. Quantitative modelling of the specific configuration for LDEF has been developed; for the meteoroid fluxes, LDEF's orbit randomizes directional effects, but for orbital debris its stabilization should lead to a more recognizable angular distribution. Both the size distribution and average meteoroid velocity could be deduced in principle if the distribution of orbital particulates were characterized. Because of the range of possible solutions, though, we need, as additional input, data on *temporal changes* in the flux (i.e. passes through specific Earth-bound orbits of particles) and especially *chemical evidence* of the residues.

Temporal evidence on LDEF from the interplanetary dust experiment (IDE) (Singer *et al.* 1984) does give clear evidence of Earth orbital particulates but, because it is a threshold sensor, the results apply to the smaller *ca.* 5 μm particulates. But are the particulates orbital micro-debris (Mulholland *et al.* 1991, Simon *et al.* 1994), or are they natural particulates captured into Earth orbit (McDonnell *et al.* 1992)? Chemical evidence is clearer when residues *can* be identified, but 70% show no residues (Hörz *et al.* 1991). Nevertheless, the negative picture in residue analysis is, in fact, positive evidence for high velocities which argues for natural unbound impactors. Both Earth-captured asteroidal and space debris sources are viable candidates for this regime.

Modelling of the mainstream meteoroid population from the LDEF data in the larger millimetre region calls for a geocentric velocity of 20 km s^{-1}; for the source, meteoroids of cometary origin are demanded. Space debris in this region is minor, and yet a 2:1 north-to-south flux ratio (referring to directions left and right along the trajectory) is seen. 'Wiggles' in the distribution, exceeding the statistical fluctuations must also be explained, and in the work of McBride *et al.* (1994) the access during LDEF's exposure to specific cometary orbital plane crossings and to meteoroid streams has given clues. Though perturbations lead to a precession of the orbit at 8° per day, LDEF's annual cycle is almost reproduced

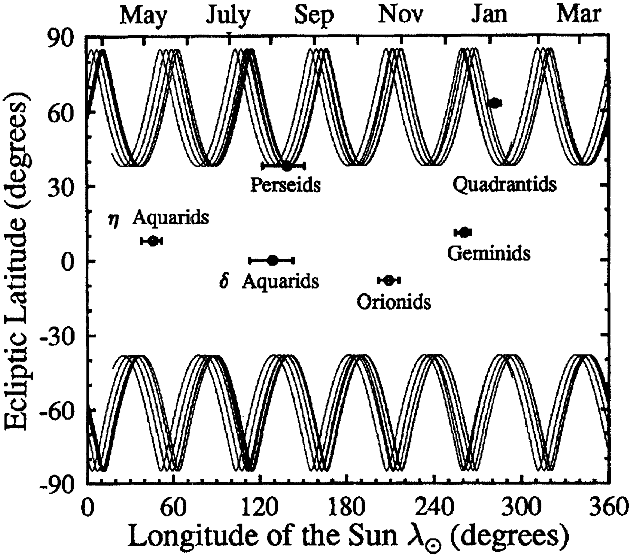

Figure 3. LDEF's exposure to meteoroid sources; though precession rapidly swings LDEF's orbit at 8° per day, the year-cycle is almost reproduced, leading to selective effects on impact rates for LDEF's different faces. The exposure of the LDEF North and South faces is shown relative to key meteoroid streams.

in successive years relative to the exposure of the north and south faces to the sources considered (figure 3). Because of LDEF's precession history, even over 5.76 years its exposure record may not lead to a meaningful average of the (seasonal) sources on a *specific face*. The case for space debris is not yet fully demonstrated as dominant; in any size region, a figure of 15% has been used as an upper limit for the space debris from several key chemical experiments (McDonnell *et al.* 1993*a*).

In earlier satellite experiments on the HEOS II satellite, real time micro-particle detectors showed flux rates similar, in terms of fluctuations, to the IDE detectors. In an era before the awareness of space debris, these were interpreted as fragmentation of natural particulates in the near-Earth environment such as the fireballs we see fragmenting in the atmosphere (Fechtig 1976). In less catastrophic interaction with the Earth they would release showers of dust into geocentric orbit. We must exercise caution therefore in explaining orbital particulates as either space debris or natural in origin; we could have a mixed environment.

(*b*) *Deep space and outer Solar System*

From Pioneers 8 and 9 (Berg & Grün 1973) the interplanetary flux at *ca.* 10^{-12} to 10^{-10} g was first determined by natural impact plasma coincidence techniques. An apex-to-antapex flux ratio (measured relative to the Earth's heliocentric motion) is surprisingly modest at 10:1 compared with meteoroid studies which show an analogous dawn-to-dusk ratio of 100 to 1000 (Taylor 1994). The motion of the heliocentric cloud relative to the Pioneer 8 and 9 detectors is required to be relatively isotropic; hence only moderate eccentricity orbital differences and orbital inclinations can pertain. Support for a prograde low eccentricity and inclination distribution is clear, but only at these small sizes.

Exploring the differing heliocentric regions we see Pioneers 10 and 11 (Humes

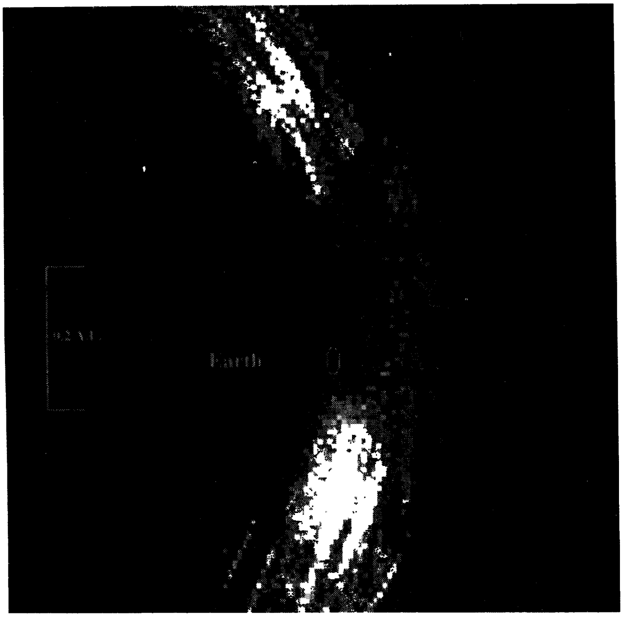

Figure 4. Spatial distribution of asteroidal grains modelling in the Earth's heliocentric orbital plane near 1 AU after release from the Hrayama family. The 5:6 locking resonance with the Earth's orbit leads to a build up just outside 1 AU.

1980) exploring the outer Solar System with penetration detectors of 25 μm thickness; the impacting flux remains puzzlingly high at large heliocentric distances compared to that predicted from impact plasma detectors on Helios I which explored the inner solar region to 0.3 AU (Grün *et al.* 1980). A heliocentric dependence of $1/r^{1.3}$ from the Helios data supports the concept of a zodiacal cloud spiralling in under Poynting–Robertson drag but may not describe the situation fully at all sizes. The β particle parent body source population, perhaps at *ca.* 0.1 AU (Grün *et al.* 1985), is dominated by masses of 10^{-5} g. This population can acquire source material decaying under Poynting–Robertson drag from either asteroids or comets. Looking at the Pioneer 10 and 11 data, however, we find that flux rates actually increase a little at 2 and 4 AU, but the continued high flux rate beyond the asteroidal belt will probably demand comets as the major source material.

Ulysses data does not answer questions on asteroids as a source but it has discovered streams now clearly identified with the Jupiter system and – for the first time – interstellar particles (Grün *et al.* 1993). This source of particulates has created a high level of excitement because it is the first evidence of interstellar matter available within the Solar System. As to our immediate question as to the major sources of matter within the inner Solar System, we must remember the very small dimension of these interstellar particulates. In the context of the mass balance and erosion in the inner Solar System we can still safely confine our attention to asteroids and comets.

4. Asteroids versus comets: competitive and complementary sources

Cometary fragmentation and grain dynamics are well studied by remote telescopic observations; even the unseen larger particulates they release are later

Table 1. *Orbital parameters affecting selective gravitational attraction by the Earth. Asteroids are highly favoured and Dermot's resonance locking (figure 4) could enhance this further.*

sources	comets		asteroids
	short period	long period	
	e = low $\langle i\rangle = 20$ $q = 0.5$–5 AU	e = high i = random $q < 1$ AU	e = low i = low
orbitally decay products at 1 AU	e = very low $\langle i\rangle = 20$ $q = 1$ AU	e = medium i = random	e = low i = low $q = 1$ AU
Earth capture efficiency	moderate	poor	high
size range dominant:			
small	44	4	444
large	4	4	4

sampled (albeit with selection effects) within the meteoroid and fireball population which we detect in the Earth's atmosphere. The case for their emission of large grains is well demonstrated and can be characterized in a semi-quantitative fashion. Undetermined yet is the dispersal in streams, fragmentation in streams and quantitative assessment of the (time varying) source generation rates. But the effect of this on the dispersal mechanisms lets us build a good picture of the orbital eccentricities and inclinations (table 1).

Supporting the importance of asteroidal sources, significant advances in modelling have been performed (Dermott *et al.* 1992, 1994*a*,*b*). Earlier work by Jackson & Zook (1989) had demonstrated resonance trapping by particles spiralling in from the asteroidal belt. Dermot's modelling (figure 4) illustrates graphically the expected concentration of micro-particles temporarily trapped for some 10^3 to 10^5 years in a 5:6 resonance with the Earth. The chances of capture by the Earth could be much enhanced by the additional concentration provided by this reservoir, not only because of enhanced concentration at 1 AU, but also because their inclination and eccentricity could be favourable for capture.

The space impact data on LDEF showing very high east-to-west ratios at micron dimensions could be partially explained by Earth capture of an asteroidal component rather than Earth orbital space debris; the low approach velocity ($V_\infty \sim 5\ \mathrm{km\ s^{-1}}$) would lead to a geocentric velocity not much greater than the escape velocity for the Earth ($10.8\ \mathrm{km\ s^{-1}}$) at LDEF's altitude; a significant fraction could be captured by atmospheric aerodrag, which would selectively act in favour of asteroids rather than comets. Larger particles, fragmenting during aerocapture, could be dispersed in a plane, thus having the same characteristics as sources of the time varying space debris orbital plane multiple interceptions (Simon *et al.* 1994).

Table 2. *Strawman payloads showing instrument functions for the Rosetta mission currently scheduled to intercept a target comet such as Schwassman Wachmann III. Launch for this mission could be in 2003.*

orbiter	M/kg	P/W	lander	M/kg	P/W
remote imaging system	20	15	gamma-ray spectrometer	0.9	3
VIS and IR mapping spectrometer	23	15	alpha-proton-X-ray fluorescence spectrometer	1	5
neutral gas and ion mass spectrometer	15	15	neutron spectrometer	4	1
cometary matter analyser	14	20	*in situ* imaging system	1.5	2
scanning electron microprobe	13	22	accelerometer	2	5
dust flux analyser	2.5	1	permittivity probe	5	2
plasma investigation	2.5	3	evolved gas analyser	3	5
total	90		total	7.5	

5. Cometary rendezvous: the Rosetta mission

Glimpses of comets during fly-bys are inevitably limited in terms of understanding the cosmogony of the Solar System despite the quantum leap in space capabilities. The modest number of comets able to be studied by space missions will also limit our understanding also, but the extreme importance attached to 'ground truth' and the calibration, provided by direct exploration, of the vast body of remote sensing data cannot be underestimated. This calibration extends, in a sense, the applicability of the expensively acquired cometary space mission data from the two target comets to the entire observable population. Also, very significant, is the concentration of scientific intellect and expertise on the modelling of cometary physics, as in the Giotto Halley environment modelling team (Divine 1981). Instrumentation is planned in the Rosetta mission based upon the 'strawman payload' (table 2) for an orbiter and a surface impactor/lander. The current target Schwassman Wachman III would be reached near to aphelion in 2008 but science operations might not be fully effective until a two-year period commencing in 2010. While we patiently await this science return, and experimental groups prepare the instrumentation needed, cometary understanding will nevertheless advance very considerably. In the Rosetta mission study activities, which were initially directed towards the return of a pristine cometary sample acquired by drilling under 'cryogenic' conditions, workshops (e.g. ESA SP 1986) demonstrated the value of modelling which was stimulated by space missions; it led, also, to the building of a laboratory comet simulation facility KOSI in Germany (Grün *et al.* 1991). The physical development of comet-like crusts with known mixtures of laboratory gas and dust there led at the KOSI facility to significant advances in understanding of cometary crust formation – at least from laboratory materials! Providing quantitative data from well-defined laboratory simulation must be the key to support such modelling and establishing parameters for computational models.

The 'minor body' aspect of planetary science is currently receiving high attention and returning quantitative data; in the planetary science space programme now ahead, which will be dominated by ESA's Rosetta mission, we will need to understand better the quantitative interrelationships between asteroids and comets.

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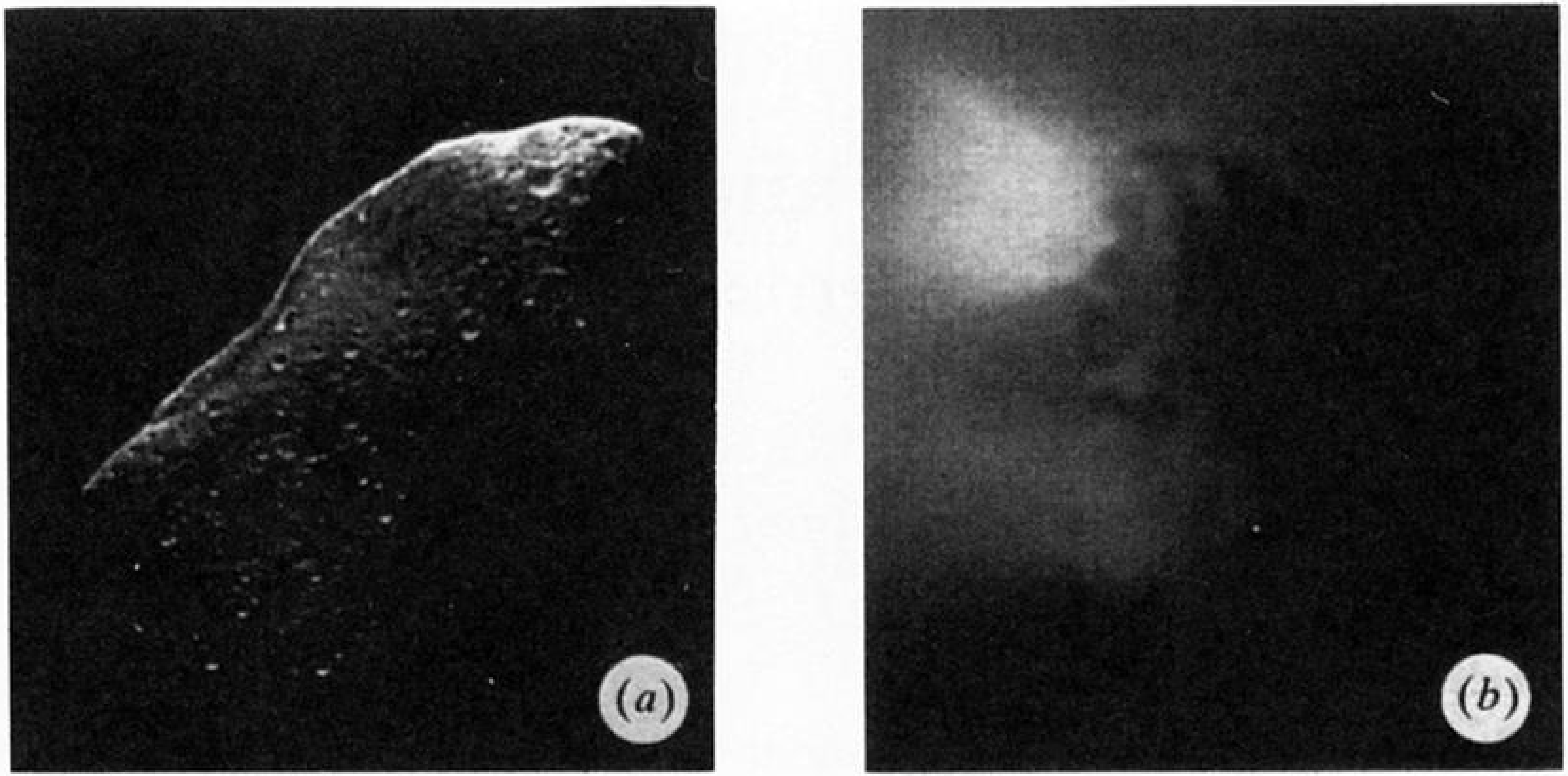
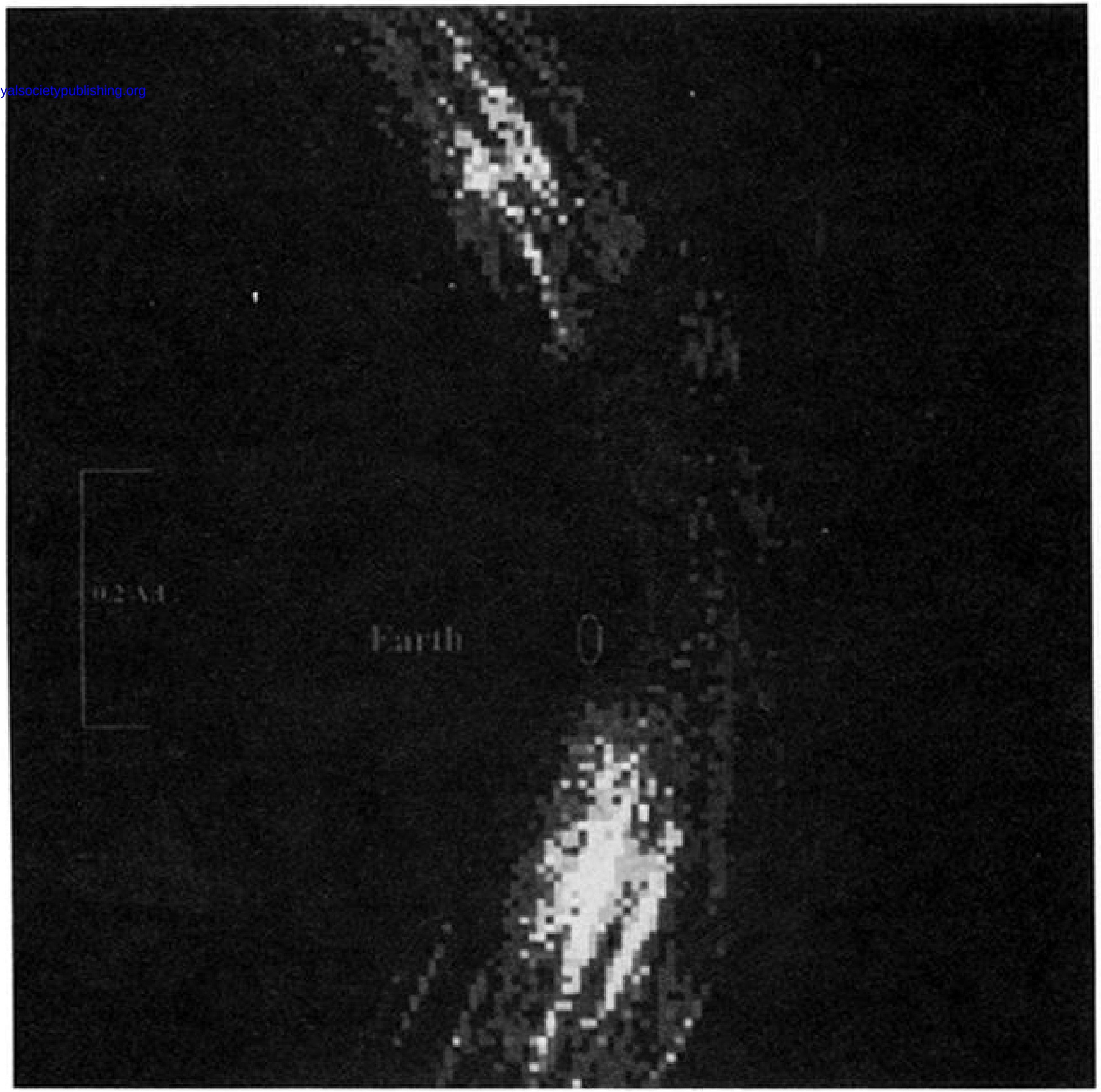
Discussion

H. FECHTIG (*Max Planck Institute for Nuclear Physics, Heidelberg, Germany*). What is the best value for the gas-to-dust ratio for Comet Halley and how does it relate to the gas-to-dust ratio of the nucleus?

J. A. M. MCDONNELL. The dust-to-gas ratio measured along the trajectory of Giotto by the DIDSY detectors is modelled, taking into account the grain expulsion velocities, back to the nucleus. This yields a dust-to-gas ratio of 2:1 if we integrate up to grain dimensions of 1 cm, but we would find the ratio increases with this integration limit. Differing substantially from that deduced from remote observations, it underlines the importance of large grains in the composition of cometary nuclei and the value of *in situ* cometary exploration. We will see this thrust continued in the newly selected Rosetta mission.



igure 1. (*a*) Spacecraft Galileo's first glimpse of asteroid Gaspra. At small dimensions crater verlapping leads to the development of a regolith despite weak gravitational forces (photo courtesy M. Belton). (*b*) Comet Halley's nucleus near to perihelion, imaged by the Halley multi-colour amera (photo courtesy H. Keller (Keller *et al.* 1986)). Craters are the result of active spots, ast or present.



igure 4. Spatial distribution of asteroidal grains modelling in the Earth's heliocentric orbital lane near 1 AU after release from the Hrayama family. The 5:6 locking resonance with the arth's orbit leads to a build up just outside 1 AU.