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INTERSTELLAR DUST IN THE SOLAR SYSTEM

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Abstract. Dust is an important component of galactic stucture and the cyclic processing of particulate matter leads to stellar and planetary formation. Though astronomical methods using analysis of dust-penetrating starlight can provide some limited information about the dust, the prospect of its *in-situ* sampling within the Solar System by spacecraft and its remote sensing by ground-based techniques open up a new field in galactic exploration.

Keywords: Interstellar-dust, meteor, meteoroid, solar-system

1. Introduction

Sampling Interstellar Dust (ISD) within the bounds of the solar system can be accomplished via several techniques – particularly *in-situ* by spacecraft, meteorites, atmospheric collections and by atmospheric impact producing meteors – yielding light emission or plasma. Evidence of the interstellar nature of such particulates requires knowledge of their dynamical, chemical or isotopic characteristics. Sampling of ISD in the solar neighbourhood will enhance our understanding of the galactic environment by fixing the solid component mass ratio and permitting the identification of dust sources. Before discussing the detection and sampling of ISD it is useful to briefly summarise some of the factors that govern dust processes on the galactic scale.

2. The Galactic Dust Environment

The re-cycling of solid material from its production in stars and subsequent evolution via molecular clouds into stellar and planetary systems is a fundamental galactic process and access to the solid aglomerations of heavy elements provides us with opportunity to gain significantly in our understanding of the controling processes in the Galaxy. Chemical sampling of grains is an important goal and some dust may retain an isotopic record of nucleosynthisis in their source stars. Discrete sources of the dust component are thought to be condensation within the expanding atmospheres of AGB (asymptotic giant branch), RGB (Red Giant Branch) carbon rich stars and Wolf-Rayat stars; protoplanetary dust discs in evolving stellar systems; and Supernova. Local sources of dust are expected in star forming regions such as the Scorpius-Centarus Association while the specific geometrical configurations of dust debris discs may govern particulate ejection in favourable (sunward) directions. Several examples of protoplanetary discs have been imaged in the Infra-Red (0.8–2.5 microns) by the HST Near infrared camera multi-object spectrometer.

The characteristics of UV, visible and IR spectra observed in astronomically long sight-lines to stars have enabled reliable models to be constructed of the constituents of interstellar dust as composed of various combinations of amorphous silicates, graphite, and PAH (polycyclic aromatic hydrocarbons) molecules, while modelling has been carried out of the processing of dust in varied galactic environments (see Frisch, 2000 and references therein).

There has been work modelling both dust evolution (Liu, 2004) and ejection (Krivov et al., 2003) in proto-planetary discs and on interstellar dynamics (Baggaley and Nuslusan, 2002; Murray et al., 2004).

The large scale dust inter-connections within the Galaxy might provide a possible mechanism for the transport of complex organic molecules (as prebiotic building-blocks) or even micro-organisms over galactic distances. Planetary systems may not be biologically isolated: for example over its history the solar system has passed through dark dust cloud complexes and giant molecular clouds. Oscillations through the galactic plane with a period of ~60 My and encounters with nearby stars may eject solid material into the solar system. In a developed stellar system large body impacts onto a bio-rich planet may cause the ejection of boulders enriched by microorganisms with subsequent erosion and fragmentation and ejection of component grains as β meteoroids. Embedded in the mantle of such grains (and so protected against irradiation from stellar UV and galactic cosmic rays) such biotic material may survive galactic transport (Melosh, 2003; Napier, 2004).

3. Flow into the Solar System

Only partial penetration of ISD into the inner solar system can occur with the heliopause at ~80 A.U. acting as filter. Small grains are coupled closely to the flow of H and He gas of the Local Interstellar Cloud (LIC), electrostatic charging (Horanyi, 1996) of grains occurs by ambient plasma and solar UV so that Lorenz forces act in the presence of the magnetic field carried by the radially expanding solar wind. In addition, absorption of solar energy produces a radiation pressure that opposes gravity: the ratio of the radiation force to gravity force, β, is independent of solar distance and depends on the grain mass and optical properties of the grain material. As illustration, for radii of 0.5 μm β~1.6 for silicate grains. In consequence, grains have non-Keplarian orbits and powerful mass-dependent filtering is imposed which (because the magnetic field depends on the solar state) is solar cycle dependent (Landgraf, 2000). For grain sizes $\gtrsim$2μm forces are gravity dominated, whereas for masses $\lesssim 10^{-17}$ kg (sizes $\lesssim$0.1 μm) complete shielding occurs.

Directional filtering of ISD will occur during their journey in the galaxy: close coupling to the local gas flow and the interstellar magnetic field (Grün and Landgraf, 2000) will exist with scale-lengths ranging from ~1 pc for dust ~1 μm to ~10^3 pc for ~50 μm: only for large grains will streaming directions with respect to the local standard of rest directly reflect source locations.

There are (at least) four populations of dust which can acquire excess energy and so yield unbound orbits within the solar system: discrimation is required to recognise that component that is truely of external origin. Dust ejected from a comet having a near-parabolic orbit (e.g. comet P/Halley has an eccentricity ~0.96) and leaving the nucleus parallel to the velocity vector can achieve speeds in excess of the solar escape speed. A population of meteoroids having speeds in excess of the parobolic limit and in the ecliptic plane are the β particles generated close to the sun by collisional interactions. Dust streams have been detected by near-Juptiter probes which result from acceleration by electric fields to high speed from origins in the Jovian system. Rare close encounters of a closed orbit particle with a major planet can result in an increase in orbital energy sufficient to yield a hyperbolic orbit.

A deposit of primordial ISD dust might be expected to have accumulated on some exposed surfaces in the outer solar system (avoiding contamination by IPD) – on Trans-Neptunian Objects and outer planetary satellites.

4. Spacecraft Detection

4.1. Impacts

In-situ sampling of ISD has been possible via the Pioneer 8 and 9, Hiten, Galileo, Ulysses, Cassini and Helios craft and the current Stardust mission. A variety of onboard instruments measured flux, speed and low-precision directions. Detectors developed by the Heidelberg Dust Group (Grün et al., 1992) of ~0.3 m^2 collecting area sense a dust particle's induced electrostatic charge via spaced grids to yield velocity and mass from ions produced as a result of impacts with a rubidium target; additionally CIDA (Cometary and Interstellar Dust Analyser) – a time-of- flight mass spectrometer with ~1%

mass resolution. Dust detection instruments require extensive laboratory calibration and the development of techniques to accelerate grains to cosmic speeds (e.g. comet encounter speeds of 63 km s^{-1} for the Giotto-Halley pass in March 14, 1986 to 6 km s^{-1} for the Stardust-Wild2 encounter January 2, 2004).

Any inner solar system sampling of ISD must have the abilty to resolve the target galactic dust in the presence of the overwhelming solar-bound interplanetary material (IPD) (Brownlee, 1985) originating in comets and asteroids. While the flux of ISD is relativly uniform within the heliosphere, the IPD form a cloud symmetrical about the ecliptic plane with spatial density latitudinal width ~30° and radial decrease with solar distance as ~ $r^{-1.3}$.

The Cassini and Helios probes measured the near-ecliptic ISD flux (see Altobelli, 2003) but especially ideal was the trajectory of Ulysses which used Jupiter gravity swing-by to achieve an orbit at 89° ecliptic inclination with aphelion distance of ~5 A.U. Because of the ability to reach large ecliptic latitudes and large solar distances the proportion of ISD to IPD improved greatly and the ability to discriminate prograde from retrograde particles isolated a clear interstellar component.

4.2. Sample-return

The Stardust probe was launched February 7, 1999 to secure ISD collection and Earth return. The major feature of the mission is to capture both cometary grains from the coma of comet Wild2 as well as ISD by decelerating grains from their craft-comet impact speed (6 km s^{-1} for comet and ~25 km s^{-1} for ISD for particular collection orbit phase) and so to secure grains intact and undamaged by the procedure. Two periods of exposure to ISD, avoiding exposure to β meteoroids were planned – when the vehicle tracked parallel to and downstream to (to reduce the impact speed to a minimum) the ISD inflow: 110 days on Orbit 1 (after gravity assist via Venus and Earth the Stardust mission having three solar orbits) of the mission Feb–May 2000; and on Orbit 2 136 days Aug–Dec 2002. These periods were prior to comet flyby on Jan 2, 2004. During the mission shields were in place to protect the main spacecraft during encounter with the cometary dust coma. After comet flyby the dust capture aerogel was stowed into the sample return capsule to await Earth re-entry Jan 15, 2006 (Kissel et al., 2004).

5. The Earth as a Detector of ISD

ISD and Pre-solar grains – recognisable by the presence of elements with non-solar isotopic ratios have been studied in meteorites (Mostefaoui et al., 1998; Hoppe and Zinner, 2000) and stratospheric aircraft collections (Messenger et al., 2003). Laboratory studies of such material over the last few years has opened up an important new tool in galactic dust astronomy. Isotopic and structural studies making use of new developments in ion probes (Nittler, 2003) have enabled specific minerals (e.g. silicates – olivenes, pyroxenes, Diamonds; Graphite; Silicon Carbide; Spinel ($MgAl_2O_4$); and Carborundum (Al_2O_3)) to be associated with specific sources – either stellar ejection or supernovea (e.g. Nittler et al., 1995).

As a solid grain decelerates in the Earth's atmosphere enough heating may occur to generate sufficient light or ionisation to permit detection as a meteor. The lower limit for unimpeded access to the solar system of ~2 μm for spacecraft data (also the approximate upper limit set by statistical sampling but also detector saturation or indeed damage) is below the limit of ~10 μm (dependent on speed) for detection as a meteor. This limit arises because during the interaction of a meteoroid of size less than this value the radiation rate from the surface area of the acquired kinetic energy is greater than the energy that goes into body heating and incomplete ablation occurs (Rietmeijer, 2002).

The effective collecting area for a ground-based single sensor (camera or radar) when using the atmosphere as a detector is of order 10^3 km^2 (depending on the technique used). Interestingly, this much larger area nearly compensates for the larger flux of smaller grains available for spacecraft detection because of the mass distribution characteristics, so that the actual detection rates of ISD by the quite different techniques are of the same order.

6. Meteor Orbits

Influxing meteoroids larger than the micrometeoroid limit dissipate kinetic energy via atmospheric interaction to yield columns of excited species – that can be sensed by visual, photographic, image intensifier, CCD – and also ionisation that can be sensed by radar. By remote sampling such a column at separated points along the trail the atmospheric trajectory of the ablating meteoroid in the atmosphere can be delineated and from that the path in space. Since the measurement is made on a moving platform and performed in a gravity field, several effects need accommodating: the rotation of the Earth – the motion of the station varies with latitude; deceleration in the atmosphere – the pre-entry needs fixing; the modification of the space motion in the gravitational field of the Earth; and the orbital motion of the Earth. Employing these corrections provides the path outside the sphere of influence of the Earth and so fixes the heliocentric orbit. It is in the dynamical measurements for which trajectory-sensing meteor surveys are especially valuable. Several stages in the development of advancing techniques can be identified in the provision of evidence by meteors for ISD.

6.1. VISUAL METEORS WITHOUT INDIVIDUAL ORBITS

The solar parabolic speed at the Earth varies from 41.4 to 42.8 km s^{-1} depending on the Earth's orbital position and therefore date. The atmospheric speed depends on the Earth's orbital speed, the particle's energy increase in the Earth's gravity field and the relatively minor effect of the observer's latitude-dependent motion due to the Earth's rotation. The atmospheric speed to an observer depends on the elongation of the meteor's radiant from the Earth's Apex direction and varies from 72.8 km s^{-1} for zero elongation to 16.4 km s^{-1} for 180°. In the 1920s and 30s campaigns provided calalogues of estimates of individual topocentric speeds and radiants in attempts to establish whether a significant proportion of speeds so determined indicated solar hyperbolic speeds. Using a single station a measurement of angular speed and visible track elevation together with an assumed mean height will provide approximate range and hence linear speed; an estimate of the radiant provides the elongation from the Earth's Apex. Catalogues complied by Von-Niessel and Hoffmeister in the 1920s (see the discusion in Lovell, 1954) for fireballs and by Opik (1941) who analysed the Harvard Arizona campaign suggested that a large proportion of Earth-impacting visual objects were extra-solar in origin.

The problem of assessing the reliability of such influx data rests primarily with velocity uncertainties: using the idea of an energy limit to fix Apex elongations and deduced Earth impact speeds, the precision required for speed could not be achieved using the techniques (like the ingenious rocking mirror method divised by Opik in the 1930s Harvard Arizona campaign) then available.

6.2. ORBITS

During the 1950s to 70s several photographic surveys were carried out using cameras of progressivly advanced design culminating in the Baker-Super-Schmidts. To fix the atmospheric trajectories requires a stereoscopic arrangement – two (as a minimum) cameras spaced by 10–50 km being suitable. The system limiting sensitivity achieved was $+3.5$ (for the Baker Super Schmidts) stellar magnitude, equivalent to a particle of mass $\sim 10^{-2}$ g. Prominant among such surveys were those carried out by the Harvard College Observatory (McCrosky and Posen, 1961; Hawkins and Southworth, 1961; Jacchia and Whipple, 1961).

6.3. ARCHIVED DATA

Much of the orbital data resulting from such surveys were archived by the IAU Commission 22 (Lindblad, 1995). Various analyses of these and other data sets aimed to establish the presence of an extra-solar meteoroid component expressing results in terms of the proportion of unbound solar orbits relative to the cometary-asteroidal (IPD) source population. Much of the emphasis in such data-set examinations focussed on the orbital statistical validity. Examination of the archived material covering a variety of observational techniques presented the fraction of meteoroids having energy in excess of the parabolic limit: the fraction varied with technique and analysis stringency from 0.2% to 22%. The emphasis in some reports on the low percentage of hyperbolic orbits rather obscures the fact that even a minute proportion has important consequences. The expected contribution from ISD is small compared with the foreground dense dust cloud so that meteor inflow measurements on the Earth are necessarily dominated by the overwhelming flux of particles making up the solar system dust cloud. Depending on the uncertainties in orbit determination, a true extra-solar minor component may be mistaken for an outlier of the major population – particularly if no other parameter (e.g. directional) is simultaneously available.

The hyperbolic meteoroid orbit contribution discussed in surveys did not usually address the question of the orbit geometry or possible sources. The question of the statistical significance of the measured orbit – the uncertainty of the elements – remained. For example, the problem of fixing the pre-entry speed in terms of the observed speed in the atmosphere requires the use of either a reliable model of deceleration behaviour or the use of directly measured speed changes (and noting that for a given meteoroid, the deceleration is not constant throughout the ablation interval).

7. Recent Work on Orbits and Possible Sources

7.1. ELECTRO-OPTICAL

Such photographic, image intensifier, CCD systems have limiting magnitudes of about +8 (mass ~ 10^{-4} g with the Mount Allison University group (Hawkes et al., 1997, 1999) and the University of Western Ontario group (Sarma and Jones, 1985) measuring a small but significant inter-stellar component.

7.2. RADAR

Because of the low expected terrestrial flux of ISD at 1 AU any technique that has the potential to acquire a large database of orbits is favourably placed to establish the extra-solar contribution and delineate dust sources. Radar techniques offer such a cabability with their capacity for continuous diurnal monitoring and sensitivity over electro-optical methods. Two geometries may be employed. Radial geometry scattering using a single narrow (~1°) wide radiation pattern with the ionisation created in the immediate vicinity of the ablating meteoroid (the head plasma) provides the radar reflection and the motion of the meteoroid is radial to the radar. Only a single radar employing one transmit-receive unit is required. If the aspect angle of the meteor trajectory to the beam central direction can be fixed, either by pulse-by-pulse positioning (as in e.g. the ALTAIR system Hunt et al., 2001) or using range-bin dwell time (e.g. Arecibo system Meisel et al., 2002) then the downstream direction of the ablating meteoroid can be fixed (to ~1°).

In an alternative arrangement, the reflection geometry is arranged so that radar scatter takes place over a substantial length of the ionisation column. In this transverse geometry mode the meteoroid trajectory is orthogonal to the radar line-of-sight providing substantial reflection from the phase addition of contributing sections along the trail: the meteor downstream direction is located in a direction orthogonal to the echo reflection point direction. Multiple sites (a minimum of three) are required to fix the atmospheric trajectory. The total scattered energy in the transverse geometry comes from a region having a length of approximately one Fresnel zone length, $(R\lambda/2)^{1/2}$ (with R range and λ radar wavelength): the reflection geometry is similar to Fresnel diffraction at a straight-edge in the optical case. This compares with the head echo plasma size in the radial scatter geometry of a few metres so the transverse geometry echo cross-section is $\sim 10^3$ greater than the radial case. This gain in sensitivity provided by the transverse target geometry can be compensated to some degree by the antenna gain improvement provided by the use of a narrow pencil beam available with a large paraboloid and the transmiter power available with some radial geometry facilities.

7.2.1. *Arecibo*

The Arecibo 450 MHz facility uses the radial reflection geometry technique employing the large radio astronomical dish constructed within a natural topography feature and has an antenna beam directed in the general direction of local zenith (sterable) narrow enough to sense the inflow direction. The facility has been employed in searches for ISD with Meisel et al. (2002) reporting ~2% interstellar presence and indicating a supernova as a possible source. This incisive instrument, if able to delineate aspect angles and able to secure a statistically good database, should provide valuable evidence of ISD.

7.2.2. *AMOR*

This continually operating surveillance HF system employing transverse geometry is in a favourable situation to establish ISD inflow for large (compared to *in-situ* detections) grains. The AMOR (Advanced Meteor Orbit Radar) facility operates at a radio quiet geographical location in New Zealand transmitting 100 kW sampling rate 379 s^{-1} using an operating frequency of 26 MHz. The low frequency of operation combined with narrow beam (1.6° HPFW on transmitting) antennas enables a limiting sensitivity of 3×10^{-7}g (at speed 40 kms^{-1}). At the control-transmit site three antennas forming a dual base interferometer provide independent phase signals yielding echo elevation (to ~0.3°) and signals for the pre-t_0 and Fresnel Transform meteoroid scalar speed measurements (see Baggaley and Grant, 2005 this volume). Two remote sites distance ~8 km and forming an approximate right-angled triangle receive reflections from different positions on the ionization trail using similar narrow beam antennas: FM UHF links then transmit the echo data to the central control site. This geometry allows the time-of-flight orthogonal velocity components to be fixed. Verification of the scalar speed produced by the echo timing is carried out by comparison with the phase information at the control site. Regular interogation of the radar operation and rapid processing of downloaded echo signal data achieve about 90% uptime over several year's operation allowing some 10^6 individual orbits to be archived.

For any radar system, to secure the true distribution of heliocentric orbits, several observational corrections are necessary: the plasma density production dependency on meteor speed; the plasma geometry; the radar response function including antenna coverage of the celestial sphere; and the Earth collision probability for a given impacting body with specified orbital elements. AMOR has provided orbital distributions of the solar-bound dust cloud accessible at 1 AU (Galligan and Baggaley, 2004) for comparisons with the different sampling provided by dust *in-situ* detections and light-scattering methods using space-probes.

The database provides a sufficiently dense orbital element space that mapping of the extra-solar grains can be achieved. A significant feature of the orbital distribution found by AMOR is the change in velocity distribution characteristics with eccentricity, e. The de-biassed inclination distribution of orbits is quite different for well bound orbits – those with heliocentric speed < 38 – compared with those in the transition region (~38–44) and those proponderently unbound of $e > 1$ (Baggaley, 1998). The largely prograde closed orbits contrasts with the more uniform distribution (a cosine dependency is expected for a random directional inflow) for $e > 1$.

The heliocentric orbital characteristics of a solar-external stream of ISD are quite distinct. In ground-based detection of solar bound annual meteoroid streams – cometary or asteroidal – the Earth passes through a confined stream in a matter of a few days: the observed orbital elements of the population cluster around a set of values (having, in the case of origins in e.g. young comets, some residual association with the parent comet). For a stream external to the solar system it is important to know what type of heliocentric orbits would intersect the Earth: what signature would indicate an unbound influx (irrespective of the ground-based technique employed for meteor detection). The geometrical property to address is the behaviour in the solar neighbourhood of inflowing ISD on Kepler orbits. For a collimated stream of ISD particles of lateral dimension large compared with the solar system flowing into the inner solar system – what would be the characteristics of the Earth-impacting orbits? In contrast to the annual cometary streams an external largescale stream of ISD would be present all year with characteristic seasonal cyclic variations in orbital elements, geocentric speed and observed flux. We can distinguished two types of Earth encounter: a type 1 collision when an ISD particle impacts the Earth at its first (and perhaps only) node crossing and a type 2 collision when an ISD particle encouters the Earth at its second node crossing. As illustration Figure 1 (from Baggaley and Nuslusan, 2002) shows the expected behaviour using a source having a far-Sun

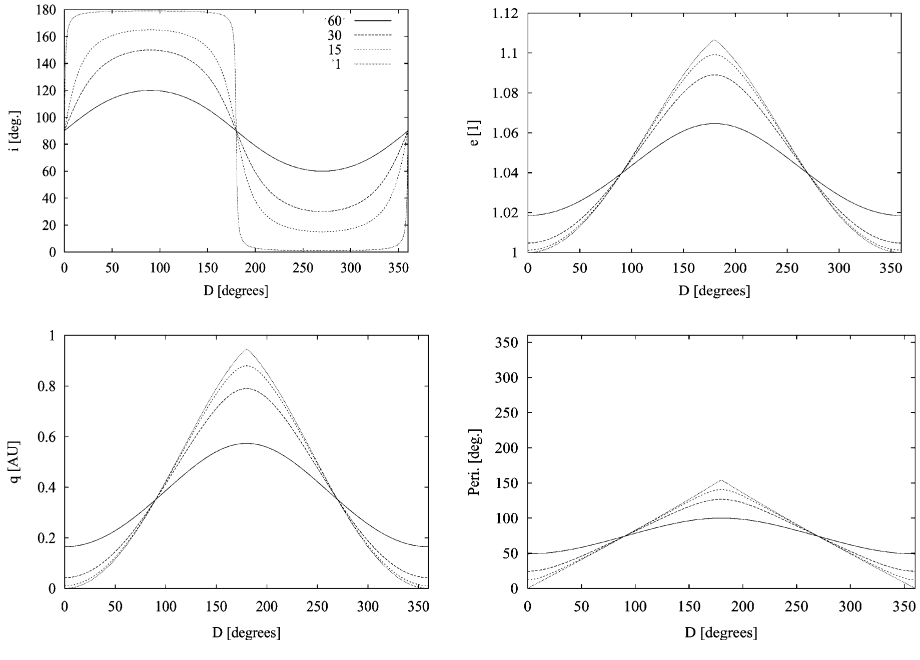

Figure 1. The changes in orbital inclination, i (upper left), eccentricity e, (upper right), perihelion distance q (lower left) and argument of perihelion, w (lower right), with longitude, D for type 2 Earth collisions for selected source latitudes β and $V_{\mathrm{inf}} = 20$ km s^{-1}. D is the difference between the ecliptic heliocentric longitudes of the Earth and external source.

heliocentric speed (for example) V_{inf} of 20 km s^{-1} and type 2 collisions: those signatures are valuable to distinguish extra-solar streams. The important feature is the quite different behaviour expected of extra-solar stream compared to a bound stream. In this way the seasonal cyclic behaviour of the observed orbital elements can be used to identify extra-solar streams and fix their far-sun inflow directions.

Using archived AMOR orbital data and from the heliocentric geometry the inflow directions of those particles with hyperbolic orbits can be mapped. From the heliocentric orbit, the upstream direction can be fixed by the asymptote – the tangent to the conic – which represents the direction in space from which the ISD approaches the solar system. Such a map using several years data of ~5×10^5 orbits shows the solar-bound and unbound heliocentric inflow directions (Baggaley, 2004) in ecliptic coordinates. Two features are evident – a general inflow of ISD at southern latitudes and a more discrete feature at ecliptic $\lambda \simeq 260°, \beta \simeq -58°$ indicating a localized interstellar source. A significant property of that localised features is the energy distribution: the distribution of heliocentric speeds of those ISD within 15° of the mean direction shows a peak at ~46 km s^{-1} (far-sun speed of 11 km s^{-1}) (Baggaley 2000, 2004). The important feature of this finding is that two pieces of evidence for ISD are available – energy (which is the parameter considered in data analyses that focused on speeds in Section 6 above) and orbital characteristics (geometry).

8. Future Directions

An exciting mission is the proposed DUNE: a solar orbiting dust telescope placed in the $L_{1,2}$ position designed with a complex of multiple grids (in contrast to the two grids arrangement used in the impact detectors employed on e.g. Cassini) to fix grain trajectory to ~1° and obtain mass spectrometer data (see Grün et al., 2001). Ground-based orbital surveillance by especially radar is a valuable tool providing large data sets for the mapping the dynamics of the larger interstellar grains.

9. Summary

For an understanding of the dominating processes that control Galaxy evolution, an important task is to fix the mass fraction of solid material in interstellar space and also the important pathways of its recycling from stellar sources to incorporation into planetary systems. Measurements made within the solar system of fluxes, mass distributions, dynamics, chemistry and source directions will provide information on past and present relations with the

LIC, dark dusty clouds and giant molecular clouds, chemical isotopic and physical structure and evolution. Inside the solar system contemporary grains can be accessed via spacecraft impacts, by sample Earth return (providing chemical and isotopic analyses), by ground-based electro-optical and (especially) radar sampling providing precise dynamical data. In addition we may seek primordial grains – inclusions in meteorites, accumulations on body surfaces in the outer solar system that await collection. The paucity of ISD forces us to operate campaigns that will provide statistically useful data – for both spacecraft for small particles and for larger meteoroid earth impact.

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