Space Sci Rev (2019) 215:43
https://doi.org/10.1007/s11214-019-0607-9

Interstellar Dust in the Solar System

Veerle J. Sterken[1,2] · Andrew J. Westphal[3] · Nicolas Altobelli[4] · David Malaspina[5] · Frank Postberg[6,7]

Received: 18 April 2018 / Accepted: 31 July 2019 / Published online: 9 October 2019

Abstract Interstellar dust from the Local Interstellar Cloud was detected unambiguously for the first time in 1992 (Grün et al. in Nature 362:428–430, 1993). Since then, great progress has been made in observing local interstellar dust in the Solar System using a variety of methods that, all together, provide complementary views of the dust particles from our local galactic neighborhood. The complementary methods discussed in this paper are: (1) *in situ* observations with dust detectors, (2) sample return, (3) observations of dust in the infrared, and (4) detections using spacecraft antennae. We review the current state of the art of *local interstellar dust* research, with a special focus on the advances made in the last ∼10 years of interstellar dust research. We introduce this paper with an overview of the definitions of interstellar dust. We describe the dynamics of the dust particles moving through the heliosphere and report on the progress made in the modelling efforts especially in the last decade. We also review the currently available *in situ* measurements of interstellar dust flux, speed, direction and size distribution from various missions, in specific from Ulysses and Cassini, and their interpretation in context of the dust dynamics studies. Interstellar dust composition is also reviewed from Cassini in situ time of flight measurements and from the Stardust sample return mission that both took place in the last decade. Finally,

Cosmic Dust from the Laboratory to the Stars
Edited by Rafael Rodrigo, Jürgen Blum, Hsiang-Wen Hsu, Detlef Koschny, Anny-Chantal Levasseur-Regourd, Jesús Martín-Pintado, Veerle Sterken and Andrew Westphal

✉ V.J. Sterken
info@veerlesterken.ch

1 Astronomisches Institut Universität Bern (AIUB), Bern, Switzerland

2 Institute of Applied Physics (IAP), University of Bern, Bern, Switzerland

3 Space Sciences Laboratory, University of California at Berkeley, Berkeley, USA

4 European Space Agency, ESAC, Madrid, Spain

5 LASP, University of Colorado, Boulder, USA

6 Institute of Earth Sciences, University of Heidelberg, Heidelberg, Germany

7 Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

also new dust measurements from spacecraft antennae are reviewed. The paper concludes with a discussion on currently still open questions, and an outlook for the future.

Keywords Dust · ISM · LIC · Meteoroids · Zodiacal dust · Interplanetary medium · Interstellar dust

1 Introduction

Because of ambiguity in the literature, we begin this review with a definition of terms. A *rock* is an object composed of one or more minerals or organic phases—this is the usual geological definition. *Interstellar dust* (ISD) consists of tiny building blocks that formed anywhere outside the solar system. We make no attempt to define tiny in this context, but perhaps a loose definition is an upper limit in diameter of $\sim$1 mm. *Interstellar Medium (ISM)-formed* dust consists of rocks that formed primarily in the interstellar medium. *Circumstellar* dust consists of rocks that formed primarily in circumstellar environments, generally in circumstellar outflows. Thus, interstellar dust consists of a mixture of circumstellar and ISM-formed dust. The definitions are not entirely orthogonal: ISM-formed dust may contain circumstellar components, or may consist of heavily modified circumstellar precursors, or both. These definitions are also not entirely satisfying—for example, ISM-formed dust could more properly be called "interstellar" dust, and interstellar dust could be called "extrasolar" dust—but we retain these definitions to maintain consistency with the nomenclature in the literature, which developed historically.

The motion of the solar system through the Local Interstellar Cloud (LIC[1]) of warm and partially-ionized gas and dust causes part of this dust to pass through the solar system, which enables us to study such "extraordinary" dust in situ, thus *nearby*. Observations of interstellar dust in the solar system have been made, so far, in five contexts.

1. Dust detectors on board the Galileo (Baguhl et al. 1996; Altobelli et al. 2005), Ulysses (Grün et al. 1993, 1994; Baguhl et al. 1996; Landgraf et al. 2000; Krüger et al. 2015; Strub et al. 2015; Frisch et al. 1999) and Cassini (Altobelli et al. 2003, 2016) spacecraft have made unambiguous detections of interstellar dust inside the heliosphere.[2] These are collectively the *in-situ ISD* observations (Sects. 3 and 4).
2. Circumstellar dust has been preserved in primitive extraterrestrial materials, in the form of so-called *pre-solar grains*. These have been identified in the matrices of primitive meteorites, in so-called *Interplanetary Dust Particles* (IDPs) collected in the stratosphere, and in micrometeorites collected from ice in Greenland and Antarctica. Because they are recognized by their highly non-solar isotopic compositions, pre-solar grains are samples of circumstellar dust: we do not yet know of an observational signature that allows us to recognize ISM-formed dust in solar-system materials. However, several lines of evidence (oxygen isotopes, crystalline fraction of silicates, D/H ratio in chondritic water, the concentration of refractory organics) are converging and point to a fraction of unaltered interstellar material in comets and undifferentiated asteroids of order 5–10% (Alexander et al. 2017). The discovery of pre-solar grains in primitive, ancient solar-system materials opened a new window on astrophysics, and demonstrated conclusively that some

[1] The Local Interstellar Cloud is a warm, low-density cloud surrounding the solar system that is located itself in a hot and even lower-density region called the "Local Bubble" (Frisch et al. 2011).

[2] The heliosphere is the region of space around the Sun that is dominated by the solar wind plasma, with respect to the ISM plasma.

interstellar materials survived the violent, hot formation of the solar system. The story is a familiar one in science, with confusion following progress following confusion, and on and on (Pais 1986, Inward bound). This paper focuses on contemporary[3] extrasolar dust only. For a review of the extensive literature on pre-solar grains, see Zinner (2014).

3. Observations of ISD in the solar system have come from a ~ 0.1 m^2 aerogel and Al foil collector on the Stardust mission that was exposed to the interstellar dust stream for 200 days. A massively-distributed search of this collector resulted in a constraint on the ISD flux independent of in-situ ISD observations, and in the identification of seven particles whose properties are consistent with an interstellar origin. Ongoing laboratory work will confirm (or not) the interstellar origin of these candidates, through measurements of the oxygen isotopic compositions (Sect. 5).
4. Isotropic foreground radiation has been detected due to the ISD, using IRAS and COBE (DIRBE) observations in the Infrared (Rowan-Robinson and May 2013) (Sect. 6.1).
5. Finally, the presence of interstellar dust has been inferred from serendipitous observations of impacts on spacecraft antennae (Sect. 6.2).

Studies of the dynamics of interstellar dust in the heliosphere for different particle properties (Sect. 2) support the understanding and interpretation of these various types of observations.

This paper reviews the current status of interstellar dust research in the solar system with an emphasis on the progress in the last decade. It focuses on new insights in the dust dynamics, in situ measurements of the interstellar dust flux and composition, interstellar dust sample return results from the Stardust mission, and indirect measurements using spacecraft antennae. Because of our somewhat arbitrary size cut, here we exclude from discussion the interstellar "asteroid" A/2017 U1 (Meech et al. 2017; Feng and Jones 2018; Zhang 2018), and the interstellar meteors (Baggaley 2000) that are currently questioned (Hajdukova et al. 2019). These subjects are reviewed in Hajdukova et al. (2019) and Koschny et al. (2019).

This book review paper is an outcome from a workshop "*Cosmic dust from the laboratory to the stars*", that was held at the International Space Sciences Institute (ISSI) in Bern (Switzerland). The topic of this paper follows up on the results from an ISSI working group on interstellar dust in the heliosphere that was held in October 1997 and whose outputs are summarized in Frisch et al. (1999) and papers in the JGR volume containing Frisch (2000).

2 Dynamics and Simulations of Interstellar Dust in the Solar System

The Sun and the planets currently move through the LIC at a velocity of $\sim 26\ \mathrm{km\,s^{-1}}$ (Witte 2004; McComas et al. 2015) in the direction of the neighbouring "G-cloud" that is less than 0.2 pc away from us and we will cross into the G-cloud within a few thousand years from now (Redfield and Linsky 2000; Redfield et al. 2004). The motion of interstellar dust passing through the solar system as a consequence of this (relative) motion has been studied through computer simulations in the context of in situ observations. We first review in Sect. 2.1 the forces acting on the ISD particles and their effects on the dust flow patterns. Then we discuss the ISD dynamics as the particles pass through the boundary regions of the heliosphere (Sect. 2.2). In both sections, we highlight the state-of-the-art modeling.

[3]This contemporary extrasolar dust may be modified by its journey through the solar system and near the Sun though.

2.1 Dynamics of Interstellar Dust in the Solar System

The three most important forces that influence the trajectories of interstellar dust moving through the solar system are solar gravity, solar radiation pressure force (Sect. 2.1.1) and the Lorentz force due to the charged particles' motion through the interplanetary magnetic field (IMF) (Sect. 2.1.2). Other forces, like planetary perturbations, Poynting-Robertson effect, Yarkovsky effect and solar wind corpuscular drag can be generally neglected (Altobelli 2004; Gustafson 1994).

2.1.1 Solar Gravity and Solar Radiation Pressure Force

The solar gravitational force on a dust particle is described by:

$$\mathbf{F}_G = -\frac{G M_\odot m_p}{|\mathbf{r}|^3}\mathbf{r} \tag{1}$$

with G the gravitational constant, $M_\odot$ the mass of the Sun, m_p the dust particle mass, and $\mathbf{r}$ the position vector of the dust particle with respect to the Sun. The solar radiation pressure force is expressed as:

$$\mathbf{F}_{SRP} = \frac{A_p Q_{pr} S_0}{c}\frac{\mathbf{r}}{|\mathbf{r}|^3} \tag{2}$$

with A_p the projected surface of the dust particle ($A_p = \pi a^2$ for a spherical particle with radius a), Q_{pr} the radiation pressure efficiency weighted by the solar spectrum, S_0 the solar flux density at 1 AU from the Sun, and c the speed of light. Q_{pr} depends on the particle optical properties.[4]

Because the solar gravity and the solar radiation pressure force are both radial and decline quadratically with increasing distance from the Sun, they can be combined in a single dimensionless ratio:

$$\beta = \frac{|\mathbf{F}_{SRP}|}{|\mathbf{F}_G|} = \frac{A_p Q_{pr} S_0}{c G M_\odot m_p} \tag{3}$$

β depends on the particle optical properties, thus on composition, morphology, and size. It is a constant value if the particles are assumed not to be altered on their path through the solar system (e.g. through evaporation) and if we neglect variations in the solar flux. The β versus mass relationship is expressed in a so-called β*-curve*, specific for each dust material, morphology, and density. Examples of such β-curves are the coloured curves in Fig. 5 (Sect. 4.3 of this paper). Silicates have lower maximum β-values than carbonaceous materials, and aggregates tend to have a "flattened" β-curve with respect to their compact counterparts. More examples of β-curves can be found in Schwehm (1976), Gustafson (1994), Kimura and Mann (2000), Kimura et al. (2003a) and Sterken et al. (2015).

The β-value of the ISD is important for its dynamics. In the absence of Lorentz forces, particles with $\beta = 1$ move through the solar system on straight trajectories because the solar radiation pressure compensates for the effects of solar gravity. Particles with $\beta < 1$ are deflected towards the Sun on hyperbolic trajectories, by the dominance of the solar gravitational over solar radiation pressure force. This is illustrated in Fig. 1 (left, from Sterken

[4] See Schwehm (1976) and Burns et al. (1979) for calculating radiation pressure efficiencies, and Silsbee and Draine (2016) and Kimura (2017) for a discussion on the radiation pressure efficiencies for ISD, applied in specific to the Stardust mission (Sect. 5).

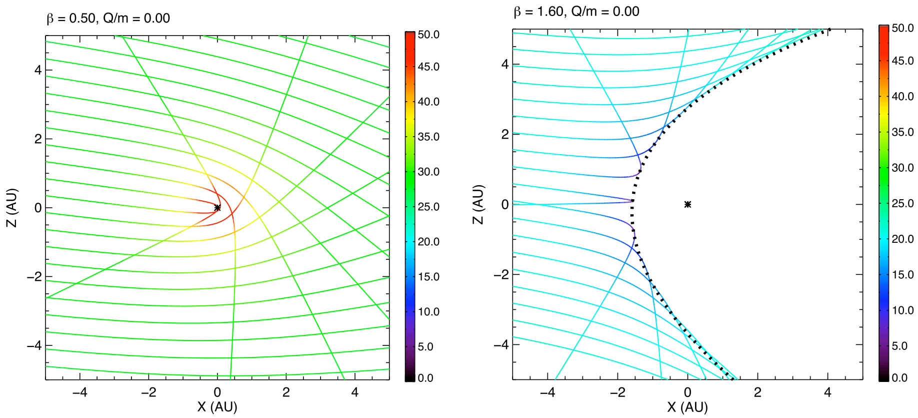

Fig. 1 Simulated dust trajectories for solar gravity and solar radiation pressure force only, for $\beta < 1$ (left) and $\beta > 1$ (right). The colors indicate the velocity of the particles with respect to the Sun (the black cross) in $\mathrm{km\,s^{-1}}$ and the dust moves from the left to the right in the simulations. From Sterken et al. (2012). Reproduced with permission from Astronomy & Astrophysics, ©ESO

et al. 2012) for $\beta = 0.5$. As the particles move out of the solar system, they accelerate again to their original speed of about 26 $\mathrm{km\,s^{-1}}$ for ISD particles from the LIC. As a result of the solar gravitational attraction, these particles form a region of *gravitational focusing* downstream of the Sun with respect to the inflow vector of the ISD (see Fig. 1, left). This gravitational focusing region is located at approximately $+79^\circ$ and -8° ecliptic longitude and latitude (Frisch et al. 1999; Landgraf 1998) as was determined from Ulysses and Galileo ISD data.[5] Because of this gravitational focusing and thus for particles with $\beta < 1$, the ISD number densities are a factor of 2–5 times larger than the undisturbed number density in the ecliptic plane, and up to a factor of 10 larger in the focusing region itself (Landgraf et al. 1999b; Strub et al. 2019). This factor depends on the distance to the Sun and on the β-value of the particles.[6] The number density enhancements can be calculated numerically or analytically. For the equations we refer to Danby and Camm (1957), Wallis (1987), Landgraf et al. (1999b). Very small and very large particles (sizes approximately below 0.1 μm or above 0.4 μm radius for silicates) belong to the size category of particles with β-values < 1, that cause such a region of gravitational focusing. However, very small particles are also deflected by Lorentz force (see Sect. 2.1.2).

Particles with $\beta > 1$ decelerate as they approach the Sun and are diverted on hyperbolic trajectories in a direction *away* from the Sun, see Fig. 1 (right), from Sterken et al. (2012) for $\beta = 1.6$. Such particles do not enter a paraboloid-shaped region around the Sun of which

[5] A newer analysis of the complete Ulysses dataset, but excluding the period where the dust flow was shifted in direction (2005, see Sect. 3.2), has resulted in a derived flow direction of $+75^\circ \pm 30$ ecliptic longitude and $-13^\circ \pm 4$ ecliptic latitude (Strub et al. 2015). This corresponds roughly to the flow direction of the interstellar helium from IBEX He data between 2009 and 2013: $+75.6^\circ \pm 1.4$ ecliptic longitude, and $-5.12^\circ \pm 0.27$ ecliptic latitude (Schwadron et al. 2015) and earlier ISD directions derived from Ulysses data by Landgraf (1998), Frisch et al. (1999), and Kimura et al. (2003b). The average speed of the ISD particles measured by Ulysses was 24 ± 12 $\mathrm{km\,s^{-1}}$ (Krüger et al. 2015), compatible with the Helium inflow speed of 26.3 ± 0.4 $\mathrm{km\,s^{-1}}$ (Witte 2004) and with earlier determination of the heliocentric ISD *inflow* speed $V_{\infty,ISD} = 25.7 \pm 0.5$ $\mathrm{km\,s^{-1}}$ from the then available Ulysses ISD data by Kimura et al. (2003b).

[6] See Sterken et al. (2013) for examples of gravitational focusing effects for $\beta = 0.5$ at Asteroid, Jupiter and Saturn distance from the Sun, in the ecliptic plane.

its size depends on the β-value of the particles. This void region in space is called the *β-cone*: its size depends on the particle properties (mass, surface optical properties) while its direction depends, like the gravitational focusing cone, on the inflow vector of the ISD.

Comparison of numerical simulations of ISD trajectories with spacecraft observations of ISD mass and velocity can constrain the particle optical properties and thus composition, provided that sufficient data are available. This method of constraining the ISD particle material properties using spacecraft data and numerical simulations, is called *β-spectroscopy* (Altobelli 2004). Landgraf et al. (1999a) used this method to conclude that the maximum β-value of the ISD particles from Ulysses data between 1992 and 1999 is between 1.4 and 1.8 for particles of mass 1×10^{-17} kg to 3×10^{-16} kg.

2.1.2 Lorentz Force

The solar gravity and radiation pressure force alone cause a static, location-dependent flow of ISD through the heliosphere. However, dust particles moving through a plasma in a radiation field like from the Sun, acquire an equilibrium charge as a result of competing currents (Mukai 1981; Horanyi 1996). They are ionized by the radiation from the Sun (*photoionization*), they lose electrons by secondary electron emission, they capture protons, and they collect electrons from the solar wind. Since the solar wind and the ionizing radiation from the Sun both decline quadratically with the distance to the Sun, these particles acquire a relatively constant nett equilibrium charge corresponding to a surface potential of about +5 V as they travel through the solar system in interplanetary space (Kempf et al. 2004).[7]

Assuming compact spheres, the net charge on the particle surface is $q = 4\pi\epsilon_0 aU$ and the charge-to-mass ratio is related to the particle size and density as:

$$\frac{Q}{m} = \frac{3\epsilon_0 U}{\rho a^2} \tag{4}$$

with ρ the particle bulk density, a its radius, U the equilibrium potential and ϵ_0 the permittivity of free space. The larger the ISD particle is, the smaller its charge-to-mass ratio Q/m is, and opposite. The smallest particles (i.e. < 0.1 µm) acquire a larger equilibrium potential than their larger counterparts due to the so-called "small-particle effect" (they have larger photoelectric yields). Kimura (2016) reviews this effect in detail and Slavin et al. (2012, Fig. 2) and Kimura and Mann (1998, Fig. 3) illustrate it in their Figures. Aggregate particles also have larger equilibrium potentials than their compact equivalents due to the small particle effect (see Ma et al. 2013). When dust particles move through different plasma environments, they also obtain different charges: sometimes largely negative (e.g. in some cases in planetary magnetospheres down to −30 V; Horanyi 1996), sometimes positive and larger than in the IMF, like in the boundary regions of the heliosphere (Sect. 2.2).

The IMF originates from the solar magnetic field that is convected outward, "frozen" in the solar wind. Because the Sun rotates, a spiral-type pattern emerges in the IMF, referred to as the "Parker spiral" (Parker 1958). The solar magnetic field can be approximated for dust trajectory computer simulations by modeling a dipole during solar minimum, a mix of magnetic field polarities at solar maximum, and a dipole with opposite polarity at the next solar minimum approximately 11 years later (Grün et al. 1994; Landgraf 2000; Sterken et al. 2012). The 22-year solar magnetic cycle dominates the IMF and because a charged

[7] Mukai (1981) calculated an equilibrium potential of +0.5 to +6 V for graphite at 1 AU and +4 to +14 V for silicate grains depending on solar wind conditions. For charging in other plasma conditions (e.g. in the heliosphere boundary regions), we refer to Sect. 2.2.

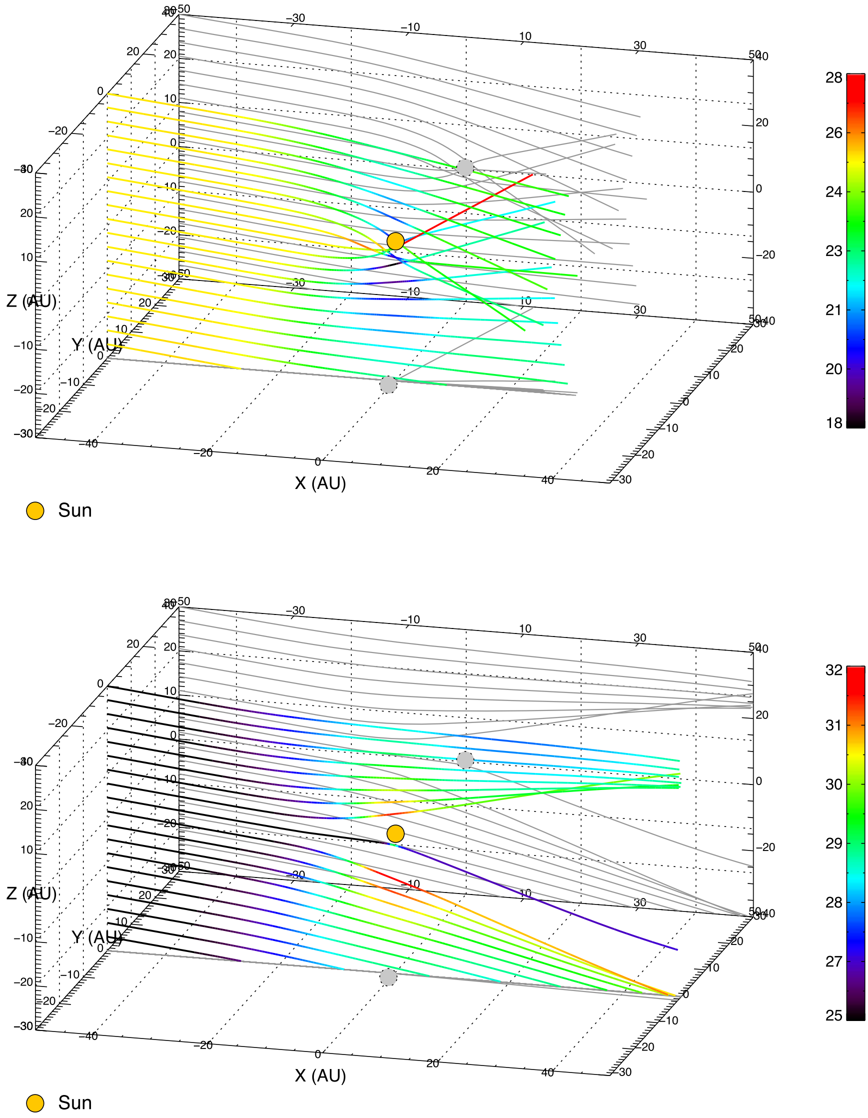

Fig. 2 Simulated dust trajectories for $\beta = 1$ and $Q/m = 1\ \mathrm{C\,kg^{-1}}$ in the focusing (upper graph) and defocusing (lower graph) phase of the 22-year solar magnetic cycle. The colors indicate the velocity of the particles with respect to the Sun in $\mathrm{km\,s^{-1}}$. From Sterken et al. (2012). Reproduced with permission from Astronomy & Astrophysics, ©ESO

particle that moves through a magnetic field experiences a Lorentz force, the 22-year solar magnetic cycle 'forces' the ISD trajectories into a *focusing* phase (during solar minimum) where the particles are focused *towards* the solar equatorial plane (see Fig. 2, upper graph), and into a *defocusing* phase at the next solar minimum, where the particles are defocused *away* from the solar equatorial plane (Fig. 2, lower graph). The magnitude and direction of the Lorentz force is determined by the particle charge-to-mass ratio (larger for small particles), the IMF direction and strength (smaller and more azimuthal at larger distances from the Sun), and the solar wind speed which is much faster (several hundreds of $\mathrm{km\,s^{-1}}$) than the ISD particle speed ($\sim 26\ \mathrm{km\,s^{-1}}$) (Witte 2004; McComas et al. 2015) with respect to the Sun. The Lorentz force is described as:

$$\mathbf{F}_L = \frac{Q}{m}(\dot{\mathbf{r}}_{p,sw} \times \mathbf{B}_{SW}) \tag{5}$$

with Q/m the charge-to-mass ratio of the dust particle, $\dot{\mathbf{r}}_{p,sw}$ the velocity vector of the dust with respect to the solar wind, and $\mathbf{B}_{SW}$ is the magnetic field vector of the IMF at the location of the dust particle. The solar equatorial plane is tilted with approximately 7° with respect to the ecliptic plane. For large charge-to-mass ratios (e.g. $Q/m \approx 10\ \mathrm{C\,kg^{-1}}$), the dust trajectories become more complicated than a mere *focusing* or *defocusing*, and density enhancements of such small ISD particles can occur at locations and during times that are not quite intuitive at a first glance. For this reason, Monte Carlo computer simulations of ISD trajectories are very helpful to understand or predict the interstellar dust fluxes measured in the solar system by in situ dust instruments (see Sects. 2.1.3 and 3.2).

The combination of gravity, solar radiation pressure force and Lorentz force leads to a modulation of the β-cones and of the zone of gravitational focusing, with time.[8] Worth to note is that during the defocusing phase of the solar cycle, the ISD particles with large enough Q/m are not only deflected away from the ecliptic plane, but they are also concentrated, as a result of Lorenz force, at higher ecliptic latitudes of ca. 10-20 AU above the ecliptic plane (see Fig. 46 in Sterken et al. 2012).

The forces acting on the ISD lead to a variable ISD size distribution that depends on space, time and particle properties like mass, morphology and optical properties (thus particle composition). For the size distribution in the ISM, generally a power-law distribution is assumed as is derived from many astronomical observations like observations of the gas phase and of absorption of starlight by the dust (e.g., see Mathis et al. 1977; Draine and Lee 1984; Weingartner and Draine 2001; Zubko et al. 2004; Wang et al. 2015). These derived size distributions are representative for long (kpc-scale) distances and the *Local* Interstellar Cloud may thus have different properties (like size distribution) from these. The filtering effect of the discussed forces in space and time and with respect to a reference size distribution is described in detail for Saturn, Jupiter and Asteroid distances in Sterken et al. (2013) and for Earth distance in Strub et al. (2019). Also for the Ulysses mission, computer simulations demonstrate the time- and space-dependent filtering of the interstellar dust size distribution, e.g. as illustrated in Fig. 12 in Sterken et al. (2015). In these studies, the filtering for small particles at the heliosphere boundary was not taken into account (we refer to Sect. 2.2 for this).

2.1.3 A Brief Review of ISD Trajectory Simulation Studies Inside the Solar System

The motion of interstellar dust in the solar system was studied and predicted long before the first *in-situ* detections in the solar system took place, with the above-mentioned physics as a basis: Bertaux and Blamont (1976) predicted that these particles should be concentrated due to gravitational focusing of the Sun (Sect. 2.1.1). Levy and Jokipii (1976) followed up on this work and postulated that the net charge that the interstellar particles would carry determines whether they can enter the heliosphere or not (see Sect. 2.2 for further discussion). Subsequently, Gustafson and Misconi (1979) and Morfill and Gruen (1979) performed the first

[8] Figures 45 and 46 in Sterken et al. (2012) visualize such "Lorentz-force-modulated β-cones".

numerical Monte Carlo computer simulations of interstellar dust trajectories that include all three the Lorentz force, solar gravity, and solar radiation pressure force and they demonstrated the focusing and defocusing effect due to the 22-year IMF cycle (Sect. 2.1.2). In 1992, the first interstellar dust particles were detected *in situ* with the Ulysses dust detector (see Sect. 3.2) by Grün et al. (1993) which prompted further numerical simulation studies of the interstellar dust flow through the solar system. Landgraf (1998, 2000) and Landgraf et al. (2000) simulated the ISD trajectories for an assumed hypothetical composition (silicate with inclusions of other chemical compounds) that is consistent with the spectral signature as observed by astronomical means (Draine and Lee 1984; Greenberg and Li 1996). Computer simulations of ISD dynamics were used to interpret the variable Ulysses ISD flux measurements from 1992 until 2000 (Landgraf 2000; Landgraf et al. 2000) and Landgraf (1998) and Frisch et al. (1999) derived the gas-to-dust mass ratio in the LIC from ISD measurements by Ulysses and Galileo to be $R_{g/d} = 40$ and $R_{g/d} = 94^{+46}_{-38}$. Czechowski and Mann (2003) studied the penetration of small interstellar dust through the heliosphere including boundary regions (inside of the heliopause). They found that a wavy current sheet can facilitate interstellar dust to enter the solar system, and suggested that beyond 40 AU, there is a stream of small interstellar dust that can enter the heliosphere at low ecliptic latitudes (see also Sect. 2.2).

Sterken et al. (2012, 2013) followed up on the dust dynamics simulation work of Landgraf (1998) by studying the flow and filtering of ISD for a broad range of dust composition assumptions, and tested a few variations of the Interplanetary Magnetic Field (IMF) models. These simulations were used for interpreting and understanding the full Ulysses dataset from 1992–2008 (Sect. 3.2). Sterken et al. (2015) also tested different descriptions of the configuration of the IMF, for which a Parker model is a sufficient approximation, but they concluded that the filtering in the heliosphere boundary regions still is a necessary additional component to be able to explain in the future the full Ulysses dataset (see Sect. 3.2). Finally, Strub et al. (2019) studied the flow of ISD onto the Earth using computer simulations, which is useful for interpreting data from missions near the Earth's orbit. Dynamical studies and the above mentioned simulations were used to predict and interpret ISD data from missions like Cassini (Altobelli et al. 2003; Sterken et al. 2012; Altobelli et al. 2016), Stardust (Landgraf et al. 1999b; Sterken et al. 2014), and Ulysses (Landgraf et al. 1999a; Landgraf 2000; Landgraf et al. 2000, 2003; Sterken et al. 2015).

2.2 Interstellar Dust Transport into the Heliosphere

Interstellar dust grains in the local interstellar medium are charged to a surface electrostatic potential of typically +0.5 to +1 V: Grün and Svestka (1996) give a detailed discussion on the grain charging in the interstellar medium. When these particles enter the heliosphere boundary regions, which have different plasma conditions from the ISM or inner heliosphere, their equilibrium potential can increase to about +8 V or +10 V (Linde and Gombosi 2000; Slavin et al. 2012).[9] Kimura and Mann (1999) elaborate on the importance of secondary electron emission for the dust transport into the heliosphere. The particles are also subject to increased magnetic field strengths and slowed down solar wind speeds in the transition regions from ISM to inner heliosphere. Linde and Gombosi (2000) calculated the filtering of small interstellar dust particles as a result of Lorentz forces in the transitional

[9] Kimura and Mann (1998) found +12 V for Silicate particles and +6 V for Carbon for particles with radius about 0.3 µm, while Alexashov et al. (2016) estimated a potential of +2 to +3 V. Ma et al. (2013) calculated higher charges for aggregates than for compact spheres (see Sect. 2.1.2)

region between the external environment and the inner heliosphere[10] during the 1996 solar minimum. They find a strong increase in filtering for grain sizes between 0.2 and 0.1 μm and below: large particles can penetrate this region freely, while small ones are rather deflected around the heliosphere instead. Note that 1996 is in the defocusing phase of the solar cycle for the outer heliosphere region where particle deflection varies significantly between solar cycle magnetic phases, see Fig. 19 in Sterken et al. (2015).[11] Based on a static MHD-model for describing the IMF and plasma conditions for calculating particle charging, Slavin et al. (2012) simulated that particles smaller than 0.01 μm are excluded completely while micron-sized particles flow freely into the solar system and particle sizes in-between are partially filtered. They calculated the global distribution of ISD inside the heliosphere as a result thereof. Time-dependence of the interplanetary magnetic field throughout the particle travel time is important for comparison with in situ data and was not yet taken into account in the model, but Slavin et al. (2012) demonstrated the variable particle charges in the boundary regions of the heliosphere and close to the Sun, and for smaller particles ("small particle effect", see Sect. 2.1.2). Alexashov et al. (2016) also modeled the ISD distribution near the interface region of the heliosphere for a time-independent magnetic field configuration based on a (static) 3D MHD model used for modelling the IMF and plasma conditions, with the aim to describe the filtering and directional deviations of the ISD near the heliosphere-LIC interface region. Their results roughly confirm earlier studies, they report on features in the heliosphere boundary regions due to the Lorentz force, and they conclude that the dust distribution near the heliopause[12] depends on the direction of the Interstellar Magnetic Field. They also calculated one time-dependent distribution of ISD in the solar system, but do not go in detail for analyzing the results, which is beyond the scope of the paper.

Recapitulating, models from Landgraf (2000), Sterken et al. (2012), Strub et al. (2019) assume a time-variable IMF polarity based on the solar wind magnetic field (through the Parker spiral) for calculating the particle trajectories during their journey through the solar system because these are moving at roughly 5.5 AU/year. Particle trajectories in these models are calculated at distances up to 50 AU from the Sun only, ignoring the effects of the heliosphere boundary regions. Particle surface potentials are assumed to be static (+5 V), as roughly justified for these distances (see Fig. 2 in Slavin et al. (2012) and Kimura and Mann (1998)). In contrast, Slavin et al. (2012) utilizes a 3D solar wind model that includes the modification of the solar wind plasma by pickup-ion mass-loading and a variable particle potential as function of the 3D solar wind plasma thermal properties. This is important in the heliosphere boundary regions that are included in the model. In contrast to the former models, this model considers two static solar magnetic polarities during the particles' journeys through and around the heliosphere.

Note that regions like the heliosphere boundary not only act as a *filter* for the size of the particles, but also for the morphology of the particles: because of their higher charges, aggregates are filtered out more easily than compact particles of the same size (Ma et al. 2013).

Once in the heliosphere, there is the second *filtering* of the dust particles near the solar system due to the higher values of the IMF strength. The Monte-Carlo based, time-dependent simulations described in Sect. 2.1.3 only take into account this second filtering

[10] The inner heliosphere is the part of the heliosphere where the solar wind dominates the plasma and is still supersonic.

[11] Figure 19 in Sterken et al. (2015) illustrates how the incoming particles move through a different phase of the solar cycle in the solar system than they did earlier when crossing the heliosphere boundary regions.

[12] The heliopause is the boundary between the solar wind dominated inner heliosphere, and the region around the heliosphere where interstellar medium plasma dominates.

near the solar system, while the (rather static) models from Slavin et al. (2012), Alexashov et al. (2016) describe the filtering near the heliosphere interface. A combination of both, including full time-dependence of all magnetic fields, is crucial for the study of the particle dynamics and for comparison with spacecraft data. Sterken et al. (2015) suggested that this may be the reason why only two distinct periods of Ulysses ISD data can be understood with the current simulations, but not the whole time-series of data at once: a full model of the heliosphere boundary combined with the solar system filtering is needed for further study.

3 In-situ Measurements and Interpretation of Interstellar Dust

3.1 Cassini, Helios, and Galileo Measurements

A fleet of interplanetary probes, carrying in-situ dust instruments, have returned measurements of the ISD flux in the Solar System, either on their way to their main destination or as secondary mission science objectives. In particular, the Helios, Galileo, Ulysses and Cassini missions have provided insights into the dynamics and composition of interstellar grains found in our Solar System at different heliocentric distances. Each of those missions was equipped with dust detectors allowing an equivalent detection sensitivity in the submicrometer size range and therefore provided comparable data. All dust detectors carried by these probes have a dust detection system based on the collection and separation of the charges (positive ions and electrons) resulting from the vaporization of the grains upon impact at hypervelocity (typically from a few up to a few tens of $\mathrm{km\,s^{-1}}$) on the detector's target. Only the Cosmic Dust Analyser (CDA) on-board Cassini and the Helios instrument were equipped with sub-systems to retrieve the elemental composition of the grains using time-of-flight (TOF) mass spectroscopy. We refer the reader to Dietzel et al. (1973), Grün et al. (1984, 1992) and Srama et al. (2004) for a detailed description of the different instruments, and in particular to Table 1 in Srama et al. (2004) for a comparison of the instruments' performances.

ISD measurements have been performed at different locations and time in interplanetary space, as well as from within the Saturnian system. In all cases, special care has been taken to discriminate impacts of interstellar grains from other dust populations. Often, a direct determination of the grain's origin based on a measurement of its impact velocity has not been possible, because of the error bar of the impact speed determination (typically, about a factor of two). Instead, the ISD identification relies on the total amount of positive ions collected upon impact combined with directionality criteria, as described in Altobelli et al. (2003, 2006); Altobelli (2004).

In the case of the Ulysses spacecraft, the ISD grain identification was somewhat easier due to the measurements performed at high ecliptic latitudes, where the abundance of IDP grains is reduced compared to the ecliptic plane, combined with the favorable spinning configuration of the instrument with respect to the direction of the ISD flow. In contrast, the analysis of the Helios, Galileo and Cassini data have been more challenging. The Helios ISD measurements were performed with the dust instrument on-board the Helios-A spacecraft between 1974, day of year 353 and 1979, day of year 002, covering heliocentric distances ranging from 0.3 AU to 0.98 AU. The spacecraft trajectory was within the ecliptic plane for an heliocentric orbital period of 190 days. The ISD measurements performed by the Galileo spacecraft were acquired between January 1990 and mid-1993 as the probe was traversing the interplanetary space within the Venus and Mars orbits (the spacecraft had to perform multiple planetary flybys in order to gain the energy to reach Jupiter). While the

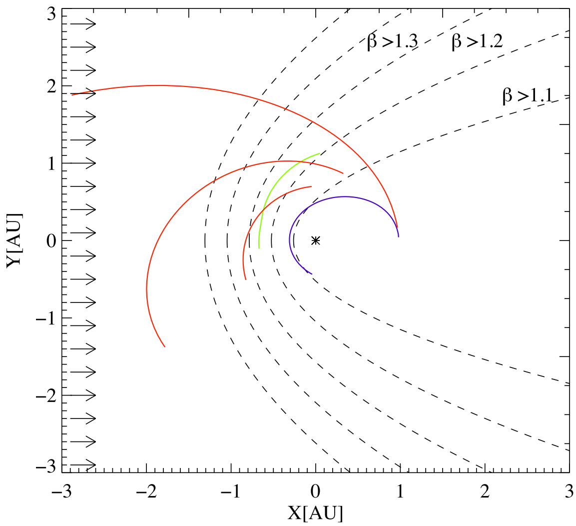

Fig. 3 Trajectory segments of the Galileo (red), Cassini (green) and Helios (blue) missions where ISD grains were detected, in the ecliptic plane. The coordinate system has the Sun as origin. The $+X$ axis is aligned with the projection on the ecliptic of the ISD downstream direction. The dotted lines indicate the ISD exclusion boundaries shaped by radiation pressure for different values of the β parameter. From Krüger et al. (2019a). Reproduced with permission from Astronomy & Astrophysics, ©ESO

dust instrument was on all the time, only three segments of the interplanetary trajectory were geometrically favorable to ISD stream monitoring. The CDA instrument was able to perform ISD measurements during the interplanetary cruise phase from 0.7 AU and 1.2 AU and during the nominal science phase around Saturn. While the Helios and Galileo dust detectors were attached to the rotating structure of their respective spacecraft, the CDA instrument can be pointed toward fixed directions as decided during the science planning of the mission (Srama et al. 2004).

Overall, a major achievement of those ISD measurements at different locations (from 0.3 to 10 AU) and time within the solar system was a confirmation of the ISD grain dynamics, as a proxy to some of their physical properties (mass distribution, radiation pressure efficiency, charge-to-mass ratio). The different segments of trajectories where ISD grain detection was achieved are shown in Fig. 3. The overall decrease of the ISD flux with decreasing heliocentric distance (see Fig. 4) is expected due to the size dependent filtering effect of radiation pressure. ISD grain models considering various compositions and structure predict β values below 2, using Mie scattering theory and Ulysses observations (Kimura et al. 2003a). At around 1.5 AU, ISD grains must have $\beta > 1.5$ in order to be filtered out by radiation pressure—beyond 5 AU, where the Ulysses measurements were performed, and *a-fortiori* at Saturn's heliocentric distance, where Cassini measurements were performed, the filtering by radiation pressure does not reduce significantly the ISD flux, which is then measured unperturbed (however, within the fluctuations due to the Solar Activity cycle on the smaller grains sensitive to the Lorentz forces, see Sect. 2.1.2).

3.2 Ulysses ISD Flux and Direction Measurements and Interpretation

The first detection of ISD in the solar system with in situ measurements by Ulysses (Grün et al. 1993) was the beginning of a 16-year long survey of the ISD flux, mass and flow direction by one and the same mission throughout three quarters of the 22-year Hale cycle. The mission was very suited for studying the ISD dynamics because of the long observation span and because of the peculiar orbit of Ulysses with respect to the ISD flow: not only Ulysses flew out of the ecliptic plane, but it also had its orbit serendipitously almost perpendicular

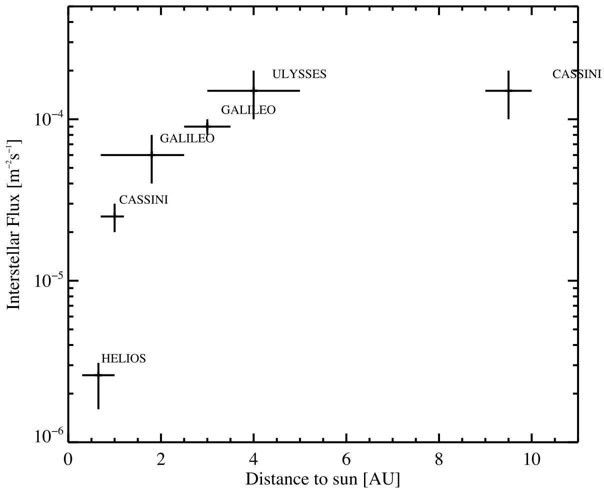

Fig. 4 ISD flux measured by the different instruments on-board Cassini (in interplanetary space and at Saturn), Galileo, Ulysses and Helios. The Helios data were taken between December 1974 and January 1980, the Cassini data were taken in 1999, the Galileo data during 3 orbit segments between January 1990 and early 1993, Ulysses data from ∼ 1992–2000 and Cassini at Saturn (∼ 10 AU) represents the average flux between mid-2004 and 2013

to the ISD inflow vector because the mission launch date was delayed with ca. 4 years from May 1986 until October 1990. Only at perihelion, the IDP particles and ISD particles came from the same (prograde) direction. During the largest part of Ulysses' orbit, ISD particles came from the retrograde direction while IDP (generally) came from the prograde direction, which facilitated their mutual distinction on a statistical basis, together with the fact that out of the ecliptic plane, IDPs are much less present than in the ecliptic.

Landgraf et al. (2003) simulated the distribution of the ISD in the solar system and compared the simulation results to Ulysses and Galileo data as far as available: the bulk ISD population had a size of 0.3 μm ($Q/m = 0.59\ \mathrm{C\,kg^{-1}}$, $\beta = 1.1$), 0.4 μm and 0.2 μm in radius, assuming the astronomical silicates β-curve from Gustafson (1994). The focusing and defocusing phase of the solar cycle were represented in the data. Krüger et al. (2007) reported on a southward shift in dust flow direction in ecliptic latitude of at least 30° as measured by Ulysses, that was unexplained until then. The full Ulysses dataset from 1992 until 2007 was analyzed in 3 subsequent papers: Krüger et al. (2015) analyzed the mass distribution of the complete data set, Strub et al. (2015) focused on the variability of the ISD flux, flow direction, mass index and flow width, and Sterken et al. (2015) interpreted these data using Monte Carlo computer simulations of the dust trajectories. Details of the ISD candidate selection criteria were slightly different, and are described in the two first papers.

Krüger et al. (2015) calculated from the Ulysses in situ data a gas-to-dust mass ratio in the Local Interstellar Cloud (LIC) of ca. $R_{g/d} \approx 231^{+102}_{-68}$ (for an assumed inflow velocity $V_\infty = 26\ \mathrm{km\,s^{-1}}$) with a local dust density in the LIC of $(1.68 \pm 0.48) \times 10^{-24}\ \mathrm{kg\,m^{-3}}$ for the same assumptions. Also, micron-sized interstellar particles were confirmed in the Ulysses data. The derived gas-to-dust mass ratio is higher than the value of $R_{g/d} \approx 94^{+46}_{-38}$ presented in Frisch et al. (1999). The latter was based on the earliest Galileo and Ulysses measurements, while the former was based on Ulysses data between 1992 and the end of 2007. A comparison of the full mission datasets is given in Krüger et al. (2019a). Krüger et al. (2015) presents a mass distribution and cumulative mass distribution for the full data set from 1992 until 2007. The total cumulative flux is ca. $7 \times 10^{-4}\ \mathrm{m^{-2}\,s^{-1}}$ (Krüger et al. 2015). Strub et al. (2015) concluded that the Ulysses ISD data indeed show the effect of the focusing and defocusing phase of the solar cycle in the flux, as was also reported in Landgraf et al. (2003) for the first subset of the data. A total shift in dust direction of $50° \pm 7°$ was confirmed that coincided with an increase of the flux by a factor of 4 in only 8 months (Strub et al. 2015). Finally, Sterken et al. (2015) studied the full β–Q/m parameter space with simulations for interpreting the Ulysses data. They concluded that the fluxes and flow directions of the bulk of the 'big' ($a > 0.2$ µm) dust particles between 1992 and 2003 in the data were compatible with the simulations for dust with $\beta > 1$ and $Q/m \approx 0.5\ \mathrm{C\,kg^{-1}}$. This corresponds well with the dominating particle population from Landgraf et al. (2003) with $\beta = 1.1$ and $Q/m = 0.59\ \mathrm{C\,kg^{-1}}$. However, such (big) particles did not explain the second half of the data provided by Ulysses: the measured shift in dust direction and the increase in dust flux were compatible to simulations of ISD with $Q/m \approx 4\ \mathrm{C\,kg^{-1}}$ instead, implying that these 'big' ISD particles are of lower density than originally assumed. The flux of the smaller particles ($a < 0.2$ µm) could not be fitted with simulations before 2003, but the shift in dust flow direction and increase in flux in 2005 were reproducible features by the Lorentz force (the small particles not being of particular low density). The authors conclude that a time-dependent filtering of the small particles at the heliosphere boundary regions may be responsible for the fact that parts of the data set can be explained, but not all the data in one go.

4 Interstellar Dust Flux and Composition from Helios and Cassini

In contrast to the Ulysses instrument, the Helios dust instrument and Cassini's CDA were equipped with a subsystem able to record time of flight mass spectra of cations of the plasma cloud generated by high-velocity impacts (Dietzel et al. 1973; Srama et al. 2004; Postberg et al. 2009a). This allows compositional in situ measurements of individual dust grains impacting the detector's target.

4.1 Helios Measurements

The mass spectra acquired by the Helios detector had a low resolution compared to detectors of later generation. A mass resolution of $5 < \frac{\Delta M}{M} < 10$ was reached with the best performances obtained between 16 and 75 a.m.u. The ISD grains were identified on the basis of their dynamical properties and an average spectrum from all ISD grains was built. Despite the poor mass resolution, two main peaks could be identified: cations with masses around 25–30 u. compatible with Mg and Al bearing silicates dominate the spectrum while a second and lower peak between 50 and 60 u. would be compatible with iron. However, a more detailed elemental composition, with relative abundances of the grain constituents could not be derived from the Helios data.

4.2 Cassini CDA Measurements

Since 2010, CDA has carried out systematic observations of interstellar dust from the Local Interstellar Cloud (LIC). Altobelli et al. (2016) showed that over 30 dust impacts recorded between 2006 and 2013 could be dynamically separated from the background flow of interplanetary dust (IDP) and the overwhelming number of icy dust originating from the Saturnian system (Hillier et al. 2007; Postberg et al. 2008, 2009b). Each of these 36 impacts provided a mass spectrum very likely showing the composition of dust from our interstellar neighborhood. Together with the few ISD candidate grains brought back to earth by the Stardust mission (Westphal et al. 2014c, and Sect. 5 of this paper), the CDA ISD dataset provided the first quantitative compositional information of contemporary interstellar dust crossing the solar system. These measurements at Saturn allowed to examine LIC dust at the largest heliocentric distance ever achieved in situ, reducing the amount of dynamical filtering as compared to former detections performed closer to the Sun. In addition, the relative position of Saturn and the Sun, with respect to the ISD stream over the sample period, permitted the detection of grains with a wide range of β-values (Sterken et al. 2012).

4.3 Cassini CDA Measurements: ISD Identification and Dynamical Properties

The identification of the faint ISD population compared to the dominant background particles native to the Saturnian system was a challenge. In particular, detection criteria based on the velocity determination from the CDA Ion Channel did not provide sufficient accuracy to distinguish Saturn bound from unbound particles. Hence, a specific detection method was implemented, utilizing an estimate of the minimum impact velocity from the presence of the oxygen and carbon signals in the TOF spectra, because the cation formation of these two species requires a certain minimum impact velocity (Postberg et al. 2009a; Fiege et al. 2014). All TOF mass spectra from dust impacts on the Cassini CAT subsystem between 2004 and 2013 were analyzed, when CDA was pointed within 50° of the reference ISD upstream direction as defined by the Ulysses and Galileo measurements (Sect. 3). This selection criterion results in over 30,000 TOF mass spectra to be investigated (Altobelli et al. 2016). From this primary dataset, most particles showed an obvious water composition signature in the spectra and thus were rejected as endogenic to the Saturnian system. For the other particles the minimum velocity with respect to Saturn was inferred and compared to the expected velocities of Saturn bound particles as well as interplanetary dust particles. A population of a few tens of particles with sufficient velocities as expected for ISD grains entering Saturn's system stood out clearly. The analysis was repeated with a control group consisting of all particles with TOF spectra coming from the opposite direction to the reference ISD upstream direction. As expected, no such high velocity dust impacts were found there.

The flux of the ISD grains was determined by fitting simultaneously the cumulative distribution of the detected particles as function of time and of the distance to Saturn. The flux value of $F = (1.5 \pm 0.1) \times 10^{-4}\ \mathrm{m^{-2}\,s^{-1}}$ derived following this approach is the heliocentric value, corrected for Saturn's motion (Altobelli et al. 2016). The directional distribution of the ISD grains suggests a well collimated flux ($< 20°$) around the reference ISD direction at Saturn. Note that the ISD time collection period benefited in 2010 of a focusing configuration of the IMF for the smaller particles (Sterken et al. 2012, 2015).

The derived mass distribution, in agreement with the Ulysses measurements, confirm the existence of grains with $\beta > 1$ with a maximum reached between 10^{-17} kg and 10^{-16} kg (Altobelli et al. 2016). By deriving the β ratio and the mass, an independent consistency check for the bulk composition was obtained. Synthetic β-mass curves were computed using Mie theory for different grain models and composition and were compared with the β-mass curve inferred from the grain dynamics (Fig. 5).

4.4 Cassini CDA Measurements: ISD Composition

Despite the relatively low mass resolution of CDA spectra ($\frac{M}{\Delta M} \approx 30$) the abundances of Mg, Fe, Ca, O, Si, and C could be determined. The dynamical separation flux coincided well with a compositional separation from the IDP background. Whereas the IDP background exhibited a wide distribution of elemental abundances, spectra of ISD grains provided specific Mg/Fe and Mg/Ca ratios indicating a surprisingly homogeneous abundance of the major rock forming metals. Each LIC-ISD grain detected by CDA contains the major rock forming elements (Mg, Si, Fe, Ca) in roughly cosmic abundances, with only small grain-to-grain variations (Altobelli et al. 2016). Hence, CDA shows there is compositional

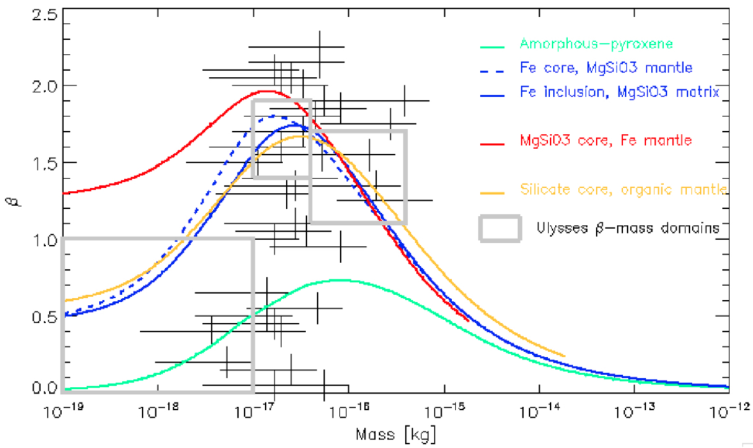

Fig. 5 This diagram shows the β-mass distribution of measured ISD grains by the Ulysses and Cassini spacecraft, as well as the expected β-mass values for different constitutive grain models. The area delimited by grey rectangles show the β-mass values as inferred from the Ulysses data, while the black crosses correspond to measurements performed by Cassini-CDA. The coloured curves show the theoretical β-mass values expected for the different grain models as listed in the plot legends. From Altobelli et al. (2016). Reprinted with permission from AAAS

homogeneity for particles of size 200 nm (Altobelli et al. 2016), as condensation products of the LIC, rather than being heterogenous samples of grains of the first generation formed around dying stars. They are homogenous because they are made of heavily processed and mixed material from different star populations. The composition observed by Altobelli et al. (2016) is different from what is observed in circumstellar dust (Leitner et al. 2012), most obviously the variation of Mg/Si, Mg/Fe is significantly smaller in the spectra obtained at Saturn (Fig. 6).

In the observed size regime, neither carbon rich grains (graphite, SiC) or pure metal or oxide grains were detected by CDA, which sets an upper limit of 8% at the 2σ confidence level for these grain species (Altobelli et al. 2016). This finding is in contrast with the isotopically and compositionally diverse populations of circumstellar dust inherited from AGB Stars and supernovae, which typically consist of silicates (e.g., olivine, pyroxene), with minor contributions (few %) of oxides (e.g., corundum, hibonite) and carbonaceous grains, mainly silicon carbide with an abundance of $> 20\%$, possibly up to 50% (Leitner et al. 2012). The upper limits for sulfur and carbon from CDA LIC-ISD grains observation indicate a substantial depletion of carbon and sulfur compared to the abundances inferred from the gas-absorption spectra of the LIC (Altobelli et al. 2016).

Although the CDA results indicate roughly cosmic element abundances of ISD grains, there seems to be a slight (20%) Si deficit (Fig. 7). A Si deficit is also supported by astronomical observations (Frisch and Slavin 2013) and can be explained by a higher abundance of either oxides and/or metals, similar to grains returned by the Stardust mission (Westphal et al. 2014c, see Sect. 5).

The dynamical analysis of the Cassini ISD grains based on plausible ranges of β-values for the 36 detections (Altobelli et al. 2016) is in good agreement with silicate particles enriched with metallic Fe. In contrast, the β-ratio of pure Fe-Mg silicates without metallic Fe enrichment cannot exceed unity, which is in disagreement with the high β-ratio of most grains above 5×10^{-17} kg. As no indications for abundant organic material is found in CDA

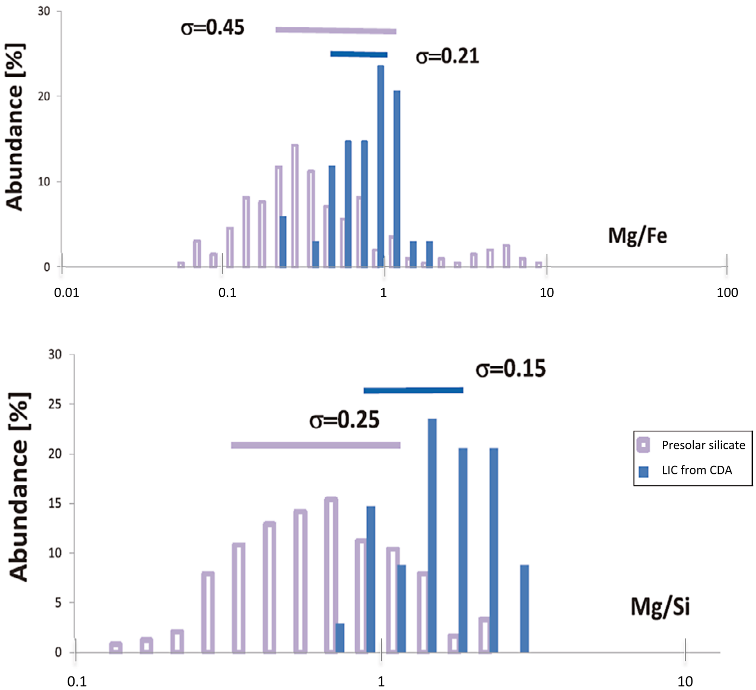

Fig. 6 Comparison of element wt% ratios in CDA ISD grains with pre-solar material. From Altobelli et al. (2016). Reprinted with permission from AAAS

ISD mass spectra it is suggested that at least some of the iron identified by CDA has to be in metallic form (Altobelli et al. 2016). However, the inferred upper limit for carbon does not exclude the presence of thin organic mantles on the ISD grains causing an increase in the β-ratio.

5 The Stardust Interstellar Dust Sample Return

In addition to a collector that returned cometary dust (Levasseur-Regourd et al. 2018, this book), the Stardust spacecraft returned a 0.1 m^2 aerogel and Al foil collector that was exposed to the interstellar dust stream for ∼200 days in 2000 and 2002. The Stardust Interstellar Preliminary Examination (ISPE) (Westphal et al. 2014b), a consortium of $>$ 50 professional scientists and $>$30,000 amateur scientists worldwide (Westphal et al. 2014a), consisted of coordinated projects to identify impacts in aerogel tiles and Al foils by optical (Westphal et al. 2014a) and SEM imaging (Stroud et al. 2014), development and implementation of novel sample preparation techniques (Frank et al. 2014), synchrotron Fourier-Transform Infrared Spectroscopy (FTIR) (Bechtel et al. 2014) and X-ray microprobeanalyses (Butterworth et al. 2014; Brenker et al. 2014; Simionovici et al. 2014; Flynn et al. 2014; Gainsforth et al. 2014), laboratory hypervelocity capture experiments (Postberg et al. 2014), numerical modeling of dust transport in the heliosphere (Sterken et al. 2014), and elemental and isotopic composition analyses of residues in Al foils (Stroud et al. 2014), concluded in 2014 with a special issue of Meteoritics and Planetary Science (MAPS) (ISPE 2014), and a Research Article in *Science* (Westphal et al. 2014c) announcing the discovery of seven

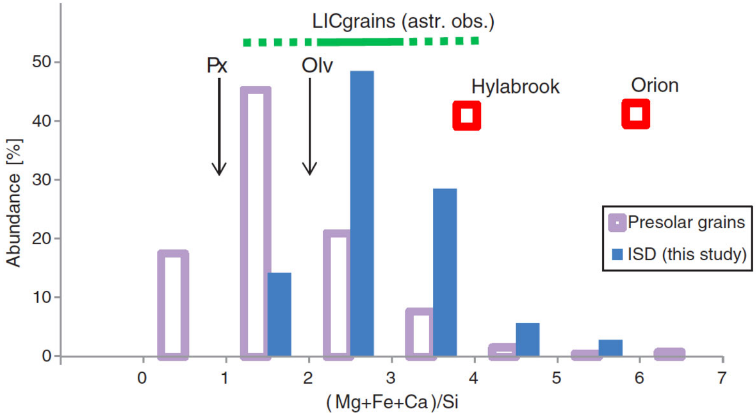

Fig. 7 Comparison of (Mg + Fe + Ca)/Si ratio histograms (in atom %) of CDA ISD grains, presolar circumstellar material, LIC ISD determined by astronomical observations and ISD returned by the Stardust mission. Intermediate between pyroxene (Px) and olivine (Olv) lies the maximum of presolar grains. An overabundance of refractory oxides in presolar grains causes a *tail* to higher values. Values for the LIC center here between 2 and 3 and are either also caused by oxides or by the presence of metallic Fe phases. The latter has also been observed in the Stardust particles Orion and Hylabrook which therefore plot at the far right. From Altobelli et al. (2016). Reprinted with permission from AAAS

particles of probable interstellar origin, as well as a measurement of the interstellar dust flux. The 2σ upper limit on the interstellar dust flux is lower than expected from dust modeling predictions, but is consistent with a large fraction of ISD consisting of particles with sufficiently large β to significantly suppress the flux at the heliocentric distance of particle collection by the Stardust spacecraft, about 2 AU.

At the conclusion of the ISPE, three impacts were identified in the aerogel collectors, and four were identified in the Al foil collectors. These particles are inconsistent in trajectory, capture speed, flux or composition with an origin as spacecraft secondaries or interplanetary dust (Westphal et al. 2014c). The two largest particles, identified in aerogel, contained crystalline silicates and so were likely to be circumstellar condensates (Westphal et al. 2014c). Both contained forsteritic olivine cores. One, Orion, also contained spinel and an iron phase that may have been consistent with nanophase iron. The other, Hylabrook, contained an amorphous Mg-bearing silicate, and also was surrounded by an Fe-bearing phase. Their measured densities were less than 1 $\mathrm{g\,cm^{-3}}$. These particles were of sufficiently low speed that they survived practically intact. Assuming that they had an interstellar origin, these particles were probably fluffy aggregates, consistent with their low overall densities, so that the ratio of light pressure force to gravitation force (β) was comparable to unity (between 1 and 1.6; Sterken et al. 2014). The third particle identified in aerogel was of sufficiently high speed that no terminal particle survived, so its composition is unknown. It was probably compact since it does not appear to have slowed significantly in the heliosphere. The four impacts in the Al foils were diverse in mineralogy and chemistry.

The crystallinity of Orion and Hylabrook was a surprise, but is not necessarily inconsistent with the astronomical constraint on the crystalline fraction of interstellar silicates (Kemper et al. 2004). If silicates are amorphized by low-energy ion bombardment in the ISM, large particles such as Orion and Hylabrook, which are much larger than typical interstellar particles, might retain crystalline cores. Indeed, their sizes alone may imply that Orion and Hylabrook are members of an entirely different population of particles than that which constitutes the bulk of interstellar dust.

Confirmation of interstellar origin of these candidates and others in the future—the search for new impacts is ongoing—depends on the ongoing development of ultrareliable techniques for measuring oxygen isotopic composition in these extremely challenging samples. Recently, Silsbee and Draine (2016) modeled the optical properties of interstellar dust, and concluded that the two large interstellar dust candidates, Orion and Hylabrook, had to have very unusual optical properties if they were interstellar. However, in a separate modeling study Kimura (2017) concluded that radiation pressure on Mg-silicate grains with nanophase Fe inclusions is sufficient high to be consistent with the Stardust observations.

6 Other Interstellar Dust Measurements

Several additional alternative techniques exist with which interstellar dust in the solar system have been measured. These are infrared observations, in situ measurements, and meteoroid observations. Of these, the in situ antenna measurements are the most promising. Other methods like PVDF detectors, or accelerometers (Thorpe et al. 2016, 2017) are too insensitive to measure interstellar dust. Interstellar meteor detections by ground-based radar systems (e.g. Baggaley 2000) are reviewed in Hajdukova et al. (2019) and Koschny et al. (2019).

6.1 Infrared Measurements

Infrared (IR) emission from dust far out in the galaxy, or in other galaxies has been used to investigate the dust properties and amounts, since the era of space infrared astronomy (e.g. the Planck and Herschel telescopes). Several attempts were also made to detect a signature of interstellar dust in, or near the solar system with infrared space telescope data. Grogan et al. (1996) modeled the infrared emission of interstellar dust in the solar system including effects like gravitational focusing for big interstellar dust, and electromagnetic forces for the smaller particles. They concluded that the prospects to find interstellar dust in the infrared data from COBE and IRAS are high enough to justify a search in the data. Indeed, a signature of an isotropic component of ISD (infrared) foreground radiation was seen in the data of the IRAS and COBE satellites by Rowan-Robinson and May (2013), by comparing models of cometary, asteroidal and interstellar dust in the solar system with infrared data from these spacecraft. The derived spatial mass-density of the interstellar dust is in agreement with values from Kimura et al. (2003a) at 1.5 AU distance from the Sun (approx. $10^{-25}\ \mathrm{kg\,m^{-3}}$), but is an order of magnitude higher than as measured by Ulysses at 4 AU. The authors argue that a study including dependence on radial distance, and a dynamical study are the next important steps to take.

6.2 Interstellar Dust Detections with Spacecraft Antennae

6.2.1 Antenna Measurements

Analysis of Voyager 1 and Voyager 2 data by Scarf et al. (1982) and Gurnett et al. (1983) determined that observed "intense impulsive noise bursts" were caused by dust grains impacting spacecraft surfaces at high velocities, thereby vaporizing and ionizing themselves and a fraction of the spacecraft surface material. Such impacts generate short-lived plasma clouds local to the spacecraft, which perturb the electric potential measured by plasma wave instruments.

While plasma wave instruments are, by their nature, not designed to detect dust grains, information concerning the mass, speed, and direction of the impacting dust can, under some circumstances, be estimated (Gurnett et al. 1983; Kurth et al. 2006; Andersson et al. 2015; Kellogg et al. 2016; Ye et al. 2016; Thayer et al. 2016; Oberc 1996; Zaslavsky 2015; Pantellini et al. 2012; McBride and Jam 1999; Collette et al. 2014, 2015, 2016). When plasma wave instruments are used as dust detectors, the entire spacecraft body surface area is sensitive to dust, resulting in count rates that can be orders of magnitude higher than those achieved by conventional dust detectors.

Dust has been detected by plasma wave instruments at the outer planets (Gurnett et al. 1987, 1991, 2004; Meyer-Vernet et al. 1986, 2009a; Pedersen et al. 1991; Tsintikidis et al. 1996; Kurth et al. 2006), near comets (Gurnett et al. 1986; Laakso et al. 1989; Neubauer et al. 1990; Tsurutani et al. 2003), and in the solar wind (Meyer-Vernet et al. 2009b; St. Cyr et al. 2009; Malaspina et al. 2014; Kellogg et al. 2016).

6.2.2 Interstellar Dust Detections and Database

Interstellar dust was identified in the STEREO and Wind plasma wave instrument data sets through a yearly modulation of the dust impact count rates (Zaslavsky et al. 2012; Malaspina et al. 2014; Wood et al. 2015; Kellogg et al. 2016).

The extensive Wind plasma wave dataset contains an observational history of the dust environment near 1 AU spanning at least two full solar cycles (Malaspina and Wilson 2016). This data set is uniquely valuable for interstellar dust studies in that: (i) it provides continuous observations over >22 years, (ii) it includes a large number of dust impacts ($>107{,}000$), and (iii) these data allow the direction that each dust grain was traveling when it impacted the spacecraft to be estimated. The Wind dust database is now publicly available on NASA's Space Science Data Facility Coordinated Data Analysis Web (Malaspina 2017).

Preliminary analysis of the Wind dust database indicates that significant changes in the flux ($6\times$) and arrival direction ($\sim 20^\circ$) of interstellar micron dust at 1 AU occurred between 2005 and 2006 (Wood et al. 2015). Analysis of Ulysses interstellar dust observations using dedicated dust detection instrumentation also reveals shifts in interstellar dust flux and direction between 2005 and 2006 (Strub et al. 2011, 2015). These observations are consistent with recent simulation results predicting a change in near-micron interstellar dust flow direction through the inner heliosphere between 2005 and 2006 due primarily to solar cycle variation (Sterken et al. 2015). The Wind database is now ready to be used with detailed modeling (Strub et al. 2019) to analyze the ISD flow near the Earth in more depth.

7 Discussion

Great progress has been made in interstellar dust research in the last decade but nevertheless many open questions remain to be solved.

7.1 Dust Dynamics and Size Distribution

The flux and flow direction of the interstellar dust has been quite well understood in its relation to the interplanetary magnetic field configurations (Sects. 2, 3.2). Also the observed shift in dust flow direction in 2006 has been identified as likely to be caused by the Lorentz force in the vicinity of the solar system. However, a complete fit from the Ulysses data (1992–2008) for one particle size and one set of material properties has not been found and a more extensive modeling, including the outskirts of the heliosphere, is required to fully understand the variations herein (Sterken et al. 2015) and to fully grasp the filtering of the dust and hence, it's original mass distribution in the LIC. New datasets from e.g. the Wind mission (Malaspina et al. 2014) are still to be understood in the context of dynamics modeling. For doing so, the required interstellar dust models up to 50 AU from the Sun, with a high enough resolution, are available already (Strub et al. 2019). Using these new data and models as a starting point will help to understand the flux and flow of interstellar dust, and in specific the relatively unexplored role of the outer parts of the heliosphere herein. Interstellar dust may as such even be used as an extra *observable* for constraining the different heliosphere models of these boundary regions of the heliosphere (Sterken et al. 2015).

7.2 Dust Composition

Analyses of the interstellar dust composition from Cassini (small particles up to 0.1 μm) and the Stardust mission (μm-sized particles for the intact captured dust, and sub-μm particles for the crater residues) conclude about a homogeneous population with the major rock forming elements (Mg, Fr, Ca, Si) in about cosmic abundances (Cassini) versus a rather diverse collection of particles (Stardust). However, Stardust observed a different ISD population than Cassini since Cassini could only detect grains with radii up to $a < 0.2$ μm whereas the Stardust ISD grains where over 50 time more massive ($a > 1$ μm). None show conclusive evidence of carbon-rich particles so far, in contrast to astronomical observations of ISD in the ISM. More research into dust composition is required to get a full image, especially concerning the presence of Carbon (or why it is not present), and the question whether Sulfide is contained in it. While Slavin and Frisch (2008) suggest a depletion of carbonaceous particles in the ISM around the heliosphere based on an overabundance of carbon in the gas phase with respect to solar photospheric abundances, Kimura (2015) proposes that carbon-rich dust particles may be altered on their path through the solar system. Sulfur in the diffuse interstellar medium is generally undepleted (Jenkins 2009) and is thus not expected to be found condensed in the form of LIC dust.

During the formation of our solar system, most presolar dust grains were destroyed or heavily processed. A minor population of circumstellar presolar grains survived processing in the protosolar disk and can be recognized by their extremely diverse isotopic composition (Zinner et al. 2007), but it is unknown whether those grains are representative of the grain populations in the interstellar medium (Frisch et al. 1999; Kimura et al. 2003a; Zhukovska et al. 2008). The homogeneous composition observed by the CDA can be explained by destruction, recondensation and equilibration processes in the ISM that homogenise an initially diverse population that started as circumstellar dust. This is supported by astronomical observations of the diffuse ISM demonstrating that the most condensable elements (atomic mass > 23) are depleted in the gas phase and hence are bound in solids, while the lifetime of interstellar grains against destruction by supernova shocks of about 0.5 Ga is much shorter than the average residence time of matter in the ISM of 2.5 Ga (Zhukovska et al. 2008). During this residence time, ISD grains frequently cycle between the hot interstellar medium (low density regions carved by supernovae), the warm diffuse medium (accessible by spectroscopic observations) and cold molecular clouds, which are star formation regions. Altobelli et al. (2016) suggest that searches for presolar interstellar grains in meteorites lead by isotopic anomalies could miss a population of isotopically inconspicuous presolar grains that recondensed in the ISM (e.g. Bradley et al. 1999; Keller and Messenger 2011).

Presolar grains have a maximum at a silicate composition intermediate between pyroxene and olivine and a tail to high values caused by a bias (overabundance) of refractory oxides. The CDA LIC ISD values center between 2 and 3 (Fig. 7). Such high values are caused either by oxides or metallic Fe, phases that have also been observed in the Stardust particles "Orion" and "Hylabrook". It should be noted, that the presolar circumstellar grain population is biased; for example there is possibly selective loss of amorphous grains or a higher fraction of resistant oxides due to metamorphic destruction on asteroids or comets. Nevertheless, it is highly unlikely that the presolar grain population initially had a distribution similar to the CDA ISD data: In this case the presolar population should have lost primarily the oxide or metal component, which is, however, unlikely, as oxides are rather more resistant against metamorphic destruction.

7.3 Dust Morphology

Also the morphology and density of the particles is not yet fully understood: the Cassini mission with its smaller particles concluded on compact interstellar dust (Altobelli et al. 2016) while the large micron-sized Stardust particles showed surprisingly low densities (Westphal et al. 2014c). Dust dynamics simulations in context of the complete Ulysses data analysis concluded on rather compact dust for the small particles ($\lesssim 0.2$ µm) and low densities for the larger particles ($\gtrsim 0.2$ µm) (Sterken et al. 2015). This is consistent with the Cassini and Stardust observations. Calibration of impact ionization instruments for low-density micron-sized dust particles has to be undertaken for obtaining a reliable and updated mass distribution, and hence, is important for the dust-to-gas mass ratio in the LIC (Sterken et al. 2016).

8 Outlook

Interstellar dust inside the solar system has been studied since 25 years, after its first unambiguous in situ detection by the Ulysses Dust Detector by Grün et al. (1993). Ulysses flew out of the ecliptic plan, but also in the ecliptic and closer to Earth there was ISD detected by in situ missions like Galileo, Helios[13] and Cassini. In the last decade, much progress has been made in the understanding the dust dynamics, its interaction with the heliosphere, and especially in its compositional analysis, by using a wide variety of complementary methods.

The full dataset of Ulysses (1992–2008) has been analysed and interpreted (Krüger et al. 2015; Strub et al. 2015; Sterken et al. 2015), new datasets from spacecraft antenna measurements became available (Malaspina et al. 2014), for the first time, contemporary interstellar dust particles were returned to Earth for further study in the laboratory (Westphal et al. 2014c), and their composition was measured in space using a time-of-flight mass spectrometer (Altobelli et al. 2016). Also, infrared measurements have confirmed the presence of interstellar dust in the solar system (Rowan-Robinson and May 2013), and although interstellar meteors are still heavily under debate (Hajdukova et al. 2019), the discovery of the first interstellar asteroid in 2017 (Feng and Jones 2018; Zhang 2018), indicates that indeed more "big" interstellar dust particles may be discovered or measured in the future with refined techniques (e.g. radar, see Koschny et al. 2019; Hajdukova et al. 2019).

The past decade, several mission concepts for *dust observatories* that would improve our knowledge of interstellar and interplanetary dust in the solar system have been proposed. These have built upon improved instrumentation. Their main asset is the combined use of the different technologies used so far. For instance, a *Dust Telescope* is a dust instrument,

[13] ISD data from Helios were sampled between 1974 and 1980, before Ulysses, but were recognized in the data and analysed only after the first Ulysses ISD detections (Altobelli 2004; Altobelli et al. 2006).

including time-of-flight mass spectrometer, combined with a trajectory detector. An *Active Dust Collector* (Grün et al. 2012) combines the dust telescope with a collection system providing two main advantages: easier identification of the particles in the aerogel tracks thanks to the trajectory sensor, and better tracking of the source of the particle and hereby a better distinction between interstellar dust and interplanetary dust. The SARIM (*SAmple Return of Interstellar Matter*) mission was proposed for ESA's Cosmic Vision 2015–2025 Programme in 2007 (Srama et al. 2009). This mission concept contained such an active dust collector and was intended to fly at the Sun-Earth Lagrange point L_2 to avoid the Earth's space debris, and would be positioned in the free solar wind. More missions for dust astronomy were proposed, like Cosmic DUNE (*DUst Near the Earth*, NASA proposal) in 2008 (Grün and Srama 2006), SARIM+ (ESA proposal, 2012), and the *Solar System Debris Disk* (S2D2) mission concept (proposal for science themes to ESA, 2013; Srama et al. 2013). NASA's Europa Mission will fly to Jupiter and has a dedicated dust detector on board (SUDA; Kempf et al. 2014) that potentially may detect and analyze the composition of ISD. Finally, the Japanese Destiny+ mission will visit the asteroid Phaeton and will carry on board an in situ dust analyzer with a mass resolution of $m/\Delta m \approx 150$ (Krüger et al. 2017). Interstellar dust measurements are foreseen (Krüger et al. 2019b). This instrument will be able to measure both cations and anions using two sensor heads in parallel, allowing O and C to be measured with a much higher sensitivity than before (using only cations during former missions), as well as S, P, SO_4, PO_4 and CO_3 (Masanori et al. 2018). With the developments in instrument capabilities and the upcoming missions (Europa Mission, Destiny+), the future looks good for further interstellar dust research and discoveries.

Acknowledgements FP received financial support from the German Research Foundation (DFG) projects PO 1015/3-1, /4-1, and ERC Consolidator Grant 724908-Habitat OASIS.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

C.M.O. Alexander, L.R. Nittler, J. Davidson, F.J. Ciesla, Measuring the level of interstellar inheritance in the solar protoplanetary disk. Meteorit. Planet. Sci. **52**, 1797–1821 (2017). https://doi.org/10.1111/maps.12891

D.B. Alexashov, O.A. Katushkina, V.V. Izmodenov, P.S. Akaev, Interstellar dust distribution outside the heliopause: deflection at the heliospheric interface. Mon. Not. R. Astron. Soc. **458**, 2553–2564 (2016). https://doi.org/10.1093/mnras/stw514

N. Altobelli, Monitoring of the interstellar dust stream in the inner solar system using data of different spacecraft. PhD thesis, Ruprecht-Karls-Universität Heidelberg (2004)

N. Altobelli, S. Kempf, M. Landgraf, R. Srama, V. Dikarev, H. Krüger, G. Moragas-Klostermeyer, E. Grün, Cassini between Venus and Earth: detection of interstellar dust. J. Geophys. Res. Space Phys. **108**, 8032 (2003). https://doi.org/10.1029/2003JA009874

N. Altobelli, S. Kempf, H. Krüger, M. Landgraf, M. Roy, E. Grün, Interstellar dust flux measurements by the Galileo dust instrument between the orbits of Venus and Mars. J. Geophys. Res. Space Phys. **110**, A07102 (2005). https://doi.org/10.1029/2004JA010772

N. Altobelli, E. Grün, M. Landgraf, A new look into the Helios dust experiment data: presence of interstellar dust inside the Earth's orbit. Astron. Astrophys. **448**, 243–252 (2006). https://doi.org/10.1051/0004-6361:20053909

N. Altobelli, F. Postberg, K. Fiege, M. Trieloff, H. Kimura, V.J. Sterken, H.W. Hsu, J. Hillier, N. Khawaja, G. Moragas-Klostermeyer, J. Blum, M. Burton, R. Srama, S. Kempf, E. Gruen, Flux and composition of interstellar dust at Saturn from Cassini's Cosmic Dust Analyzer. Science **352**, 312–318 (2016). https://doi.org/10.1126/science.aac6397

L. Andersson, T.D. Weber, D. Malaspina, F. Crary, R.E. Ergun, G.T. Delory, C.M. Fowler, M.W. Morooka, T. McEnulty, A.I. Eriksson, D.J. Andrews, M. Horanyi, A. Collette, R. Yelle, B.M. Jakosky, Dust observations at orbital altitudes surrounding Mars. Science **350**, 0398 (2015). https://doi.org/10.1126/science.aad0398

W.J. Baggaley, Advanced Meteor Orbit Radar observations of interstellar meteoroids. J. Geophys. Res. **105**(10), 10353–10362 (2000). https://doi.org/10.1029/1999JA900383

M. Baguhl, E. Grün, M. Landgraf, In situ measurements of interstellar dust with the ULYSSES and Galileo spaceprobes. Space Sci. Rev. **78**, 165–172 (1996). https://doi.org/10.1007/BF00170803

H.A. Bechtel, G.J. Flynn, C. Allen, D. Anderson, A. Ansari, S. Bajt, R.K. Bastien, N. Bassim, J. Borg, F.E. Brenker, J. Bridges, D.E. Brownlee, M. Burchell, M. Burghammer, A.L. Butterworth, H. Changela, P. Cloetens, A.M. Davis, R. Doll, C. Floss, D.R. Frank, Z. Gainsforth, E. Grün, P.R. Heck, J.K. Hillier, P. Hoppe, B. Hudson, J. Huth, B. Hvide, A. Kearsley, A.J. King, B. Lai, J. Leitner, L. Lemelle, H. Leroux, A. Leonard, R. Lettieri, W. Marchant, L.R. Nittler, R. Ogliore, W.J. Ong, F. Postberg, M.C. Price, S.A. Sandford, J.A.S. Tresseras, S. Schmitz, T. Schoonjans, G. Silversmit, A.S. Simionovici, V.A. Solé, R. Srama, F.J. Stadermann, T. Stephan, V.J. Sterken, J. Stodolna, R.M. Stroud, S. Sutton, M. Trieloff, P. Tsou, A. Tsuchiyama, T. Tyliszczak, B. Vekemans, L. Vincze, J. von Korff, A.J. Westphal, N. Wordsworth, D. Zevin, M.E. Zolensky, Stardust Interstellar Preliminary Examination III: infrared spectroscopic analysis of interstellar dust candidates. Meteorit. Planet. Sci. **49**, 1548–1561 (2014). https://doi.org/10.1111/maps.12125

J.L. Bertaux, J.E. Blamont, Possible evidence for penetration of interstellar dust into the solar system. Nature **262**, 263–266 (1976). https://doi.org/10.1038/262263a0

J.P. Bradley, L.P. Keller, T.P. Snow, M.S. Hanner, G.J. Flynn, J.C. Gezo, S.J. Clemett, D.E. Brownlee, J.E. Bowey, An infrared spectral match between GEMS and interstellar grains. Science **285**, 1716–1718 (1999). https://doi.org/10.1126/science.285.5434.1716

F.E. Brenker, A.J. Westphal, L. Vincze, M. Burghammer, S. Schmitz, T. Schoonjans, G. Silversmit, B. Vekemans, C. Allen, D. Anderson, A. Ansari, S. Bajt, R.K. Bastien, N. Bassim, H.A. Bechtel, J. Borg, J. Bridges, D.E. Brownlee, M. Burchell, A.L. Butterworth, H. Changela, P. Cloetens, A.M. Davis, R. Doll, C. Floss, G. Flynn, P. Fougeray, D.R. Frank, Z. Gainsforth, E. Grün, P.R. Heck, J.K. Hillier, P. Hoppe, B. Hudson, J. Huth, B. Hvide, A. Kearsley, A.J. King, B. Lai, J. Leitner, L. Lemelle, H. Leroux, A. Leonard, R. Lettieri, W. Marchant, L.R. Nittler, R. Ogliore, W.J. Ong, F. Postberg, M.C. Price, S.A. Sandford, J.A.S. Tresseras, A.S. Simionovici, V.A. Solé, R. Srama, F. Stadermann, T. Stephan, V.J. Sterken, J. Stodolna, R.M. Stroud, S. Sutton, M. Trieloff, P. Tsou, A. Tsuchiyama, T. Tyliszczak, J. Korff, N. Wordsworth, D. Zevin, M.E. Zolensky, Stardust Interstellar Preliminary Examination V: XRF analyses of interstellar dust candidates at ESRF ID13. Meteorit. Planet. Sci. **49**, 1594–1611 (2014). https://doi.org/10.1111/maps.12206

J.A. Burns, P.L. Lamy, S. Soter, Radiation forces on small particles in the solar system. Icarus **40**, 1–48 (1979). https://doi.org/10.1016/0019-1035(79)90050-2

A.L. Butterworth, A.J. Westphal, T. Tyliszczak, Z. Gainsforth, J. Stodolna, D.R. Frank, C. Allen, D. Anderson, A. Ansari, S. Bajt, R.K. Bastien, N. Bassim, H.A. Bechtel, J. Borg, F.E. Brenker, J. Bridges, D.E. Brownlee, M. Burchell, M. Burghammer, H. Changela, P. Cloetens, A.M. Davis, R. Doll, C. Floss, G. Flynn, E. Grün, P.R. Heck, J.K. Hillier, P. Hoppe, B. Hudson, J. Huth, B. Hvide, A. Kearsley, A.J. King, B. Lai, J. Leitner, L. Lemelle, H. Leroux, A. Leonard, R. Lettieri, W. Marchant, L.R. Nittler, R. Ogliore, W.J. Ong, F. Postberg, M.C. Price, S.A. Sandford, J.A.S. Tresseras, S. Schmitz, T. Schoonjans, G. Silversmit, A.S. Simionovici, V.A. Solé, R. Srama, F.J. Stadermann, T. Stephan, V.J. Sterken, R.M. Stroud, S. Sutton, M. Trieloff, P. Tsou, A. Tsuchiyama, B. Vekemans, L. Vincze, J. von Korff, N. Wordsworth, D. Zevin, M.E. Zolensky, Stardust Interstellar Preliminary Examination IV: Scanning transmission X-ray microscopy analyses of impact features in the Stardust Interstellar Dust Collector. Meteorit. Planet. Sci. **49**, 1562–1593 (2014). https://doi.org/10.1111/maps.12220

A. Collette, E. Grün, D. Malaspina, Z. Sternovsky, Micrometeoroid impact charge yield for common spacecraft materials. J. Geophys. Res. Space Phys. **119**, 6019–6026 (2014). https://doi.org/10.1002/2014JA020042

A. Collette, G. Meyer, D. Malaspina, Z. Sternovsky, Laboratory investigation of antenna signals from dust impacts on spacecraft. J. Geophys. Res. Space Phys. **120**, 5298–5305 (2015). https://doi.org/10.1002/2015JA021198

A. Collette, D.M. Malaspina, Z. Sternovsky, Characteristic temperatures of hypervelocity dust impact plasmas. J. Geophys. Res. Space Phys. **121**, 8182–8187 (2016). https://doi.org/10.1002/2015JA022220

A. Czechowski, I. Mann, Penetration of interstellar dust grains into the heliosphere. J. Geophys. Res. Space Phys. **108**, 8038 (2003). https://doi.org/10.1029/2003JA009917

J.M.A. Danby, G.L. Camm, Statistical dynamics and accretion. Mon. Not. R. Astron. Soc. **117**, 50 (1957). https://doi.org/10.1093/mnras/117.1.50

H. Dietzel, G. Eichhorn, H. Fechtig, E. Grun, H.J. Hoffmann, J. Kissel, The HEOS 2 and HELIOS micrometeoroid experiments. J. Phys. E, Sci. Instrum. **6**, 209–217 (1973). https://doi.org/10.1088/0022-3735/6/3/008

B.T. Draine, H.M. Lee, Optical properties of interstellar graphite and silicate grains. Astrophys. J. **285**, 89–108 (1984). https://doi.org/10.1086/162480

F. Feng, H.R.A. Jones, Oumuamua as a messenger from the Local Association. Astrophys. J. Lett. **852**, L27 (2018). https://doi.org/10.3847/2041-8213/aaa404. 1711.08800

K. Fiege, M. Trieloff, J.K. Hillier, M. Guglielmino, F. Postberg, R. Srama, S. Kempf, J. Blum, Calibration of relative sensitivity factors for impact ionization detectors with high-velocity silicate microparticles. Icarus **241**, 336–345 (2014). https://doi.org/10.1016/j.icarus.2014.07.015

G.J. Flynn, S.R. Sutton, B. Lai, S. Wirick, C. Allen, D. Anderson, A. Ansari, S. Bajt, R.K. Bastien, N. Bassim, H.A. Bechtel, J. Borg, F.E. Brenker, J. Bridges, D.E. Brownlee, M. Burchell, M. Burghammer, A.L. Butterworth, H. Changela, P. Cloetens, A.M. Davis, R. Doll, C. Floss, D. Frank, Z. Gainsforth, E. Grün, P.R. Heck, J.K. Hillier, P. Hoppe, B. Hudson, J. Huth, B. Hvide, A. Kearsley, A.J. King, J. Leitner, L. Lemelle, H. Leroux, A. Leonard, R. Lettieri, W. Marchant, L.R. Nittler, R. Ogliore, W.J. Ong, F. Postberg, M.C. Price, S.A. Sandford, J.A.S. Tresseras, S. Schmitz, T. Schoonjans, G. Silversmit, A. Simionovici, V.A. Sol, R. Srama, F.J. Stadermann, T. Stephan, V. Sterken, J. Stodolna, R.M. Stroud, M. Trieloff, P. Tsou, A. Tsuchiyama, T. Tyliszczak, B. Vekemans, L. Vincze, J. von Korff, A.J. Westphal, N. Wordsworth, D. Zevin, M.E. Zolensky, Stardust Interstellar Preliminary Examination VII: synchrotron X-ray fluorescence analysis of six Stardust interstellar candidates measured with the Advanced Photon Source 2-ID-D microprobe. Meteorit. Planet. Sci. **49**, 1626–1644 (2014). https://doi.org/10.1111/maps.12144

D.R. Frank, A.J. Westphal, M.E. Zolensky, Z. Gainsforth, A.L. Butterworth, R.K. Bastien, C. Allen, D. Anderson, A. Ansari, S. Bajt, N. Bassim, H.A. Bechtel, J. Borg, F.E. Brenker, J. Bridges, D.E. Brownlee, M. Burchell, M. Burghammer, H. Changela, P. Cloetens, A.M. Davis, R. Doll, C. Floss, G. Flynn, E. Grün, P.R. Heck, J.K. Hillier, P. Hoppe, B. Hudson, J. Huth, B. Hvide, A. Kearsley, A.J. King, B. Lai, J. Leitner, L. Lemelle, H. Leroux, A. Leonard, R. Lettieri, W. Marchant, L.R. Nittler, R. Ogliore, W.J. Ong, F. Postberg, M.C. Price, S.A. Sandford, J.A.S. Tresseras, S. Schmitz, T. Schoonjans, G. Silversmit, A.S. Simionovici, V.A. Solé, R. Srama, T. Stephan, V.J. Sterken, J. Stodolna, R.M. Stroud, S. Sutton, M. Trieloff, P. Tsou, A. Tsuchiyama, T. Tyliszczak, B. Vekemans, L. Vincze, J. von Korff, N. Wordsworth, D. Zevin, Stardust Interstellar Preliminary Examination II: curating the interstellar dust collector, picokeystones, and sources of impact tracks. Meteorit. Planet. Sci. **49**, 1522–1547 (2014). https://doi.org/10.1111/maps.12147

P.C. Frisch, Foreword. J. Geophys. Res. **105**, 10237–10238 (2000). https://doi.org/10.1029/1999JA900349

P.C. Frisch, J.D. Slavin, Interstellar dust close to the Sun. Earth Planets Space **65**, 175 (2013)

P.C. Frisch, J.M. Dorschner, J. Geiss, J.M. Greenberg, E. Grün, M. Landgraf, P. Hoppe, A.P. Jones, W. Krätschmer, T.J. Linde, G.E. Morfill, W. Reach, J.D. Slavin, J. Svestka, A.N. Witt, G.P. Zank, Dust in the local interstellar wind. Astrophys. J. **525**, 492–516 (1999). https://doi.org/10.1086/307869. astro-ph/9905108

P.C. Frisch, S. Redfield, J.D. Slavin, The interstellar medium surrounding the Sun. Annu. Rev. Astron. Astrophys. **49**, 237–279 (2011). https://doi.org/10.1146/annurev-astro-081710-102613

Z. Gainsforth, F.E. Brenker, A.S. Simionovici, S. Schmitz, M. Burghammer, A.L. Butterworth, P. Cloetens, L. Lemelle, J.A.S. Tresserras, T. Schoonjans, G. Silversmit, V.A. Solé, B. Vekemans, L. Vincze, A.J. Westphal, C. Allen, D. Anderson, A. Ansari, S. Bajt, R.K. Bastien, N. Bassim, H.A. Bechtel, J. Borg, J. Bridges, D.E. Brownlee, M. Burchell, H. Changela, A.M. Davis, R. Doll, C. Floss, G. Flynn, P. Fougeray, D. Frank, E. Grün, P.R. Heck, J.K. Hillier, P. Hoppe, B. Hudson, J. Huth, B. Hvide, A. Kearsley, A.J. King, B. Lai, J. Leitner, H. Leroux, A. Leonard, R. Lettieri, W. Marchant, L.R. Nittler, R. Ogliore, W.J. Ong, F. Postberg, M.C. Price, S.A. Sandford, R. Srama, T. Stephan, V. Sterken, J. Stodolna, R.M. Stroud, S. Sutton, M. Trieloff, P. Tsou, A. Tsuchiyama, T. Tyliszczak, J. von Korff, D. Zevin, M.E. Zolensky, Stardust Interstellar Preliminary Examination VIII: identification of crystalline material in two interstellar candidates. Meteorit. Planet. Sci. **49**, 1645–1665 (2014). https://doi.org/10.1111/maps.12148

J.M. Greenberg, A. Li, What are the true astronomical silicates? Astron. Astrophys. **309**, 258–266 (1996)

K. Grogan, S.F. Dermott, B.A.S. Gustafson, An estimation of the interstellar contribution to the zodiacal thermal emission. Astrophys. J. **472**, 812 (1996). https://doi.org/10.1086/178110

E. Grün, R. Srama (Cosmic Dune Team), The Cosmic DUNE dust astronomy mission, in *European Planetary Science Congress 2006* (2006), p. 292

E. Grün, J. Svestka, Physics of interplanetary and interstellar dust. Space Sci. Rev. **78**, 347–360 (1996). https://doi.org/10.1007/BF00170821

E. Grün, H. Fechtig, J. Kissel, The micrometeorite experiment on HELIOS. Geochim. Cosmochim. Acta, Suppl. (1984)

E. Grün, H. Fechtig, M.S. Hanner, J. Kissel, B.A. Lindblad, D. Linkert, D. Maas, G.E. Morfill, H.A. Zook, The Galileo dust detector. Space Sci. Rev. **60**, 317–340 (1992). https://doi.org/10.1007/BF00216860

E. Grün, H. Zook, M. Baguhl, A. Balogh, S. Bame, H. Fechtig, R. Forsyth, M. Hanner, M. Horanyi, J. Kissel, B.A. Lindblad, D. Linkert, G. Linkert, I. Mann, J. McDonnel, G. Morfill, J. Phillips, C. Polanskey, G. Schwehm, N. Siddique, P. Staubach, J. Svestka, A. Taylor, Discovery of Jovian dust streams and interstellar grains by the Ulysses spacecraft. Nature **362**, 428–430 (1993)

E. Grün, B. Gustafson, I. Mann, M. Baguhl, G.E. Morfill, P. Staubach, A. Taylor, H.A. Zook, Interstellar dust in the heliosphere. Astron. Astrophys. **286**, 915–924 (1994)

E. Grün, Z. Sternovsky, M. Horanyi, V. Hoxie, S. Robertson, J. Xi, S. Auer, M. Landgraf, F. Postberg, M.C. Price, R. Srama, N.A. Starkey, J.K. Hillier, I.A. Franchi, P. Tsou, A. Westphal, Z. Gainsforth, Active cosmic dust collector. Planet. Space Sci. **60**, 261–273 (2012). https://doi.org/10.1016/j.pss.2011.09.006

D.A. Gurnett, E. Grun, D. Gallagher, W.S. Kurth, F.L. Scarf, Micron-sized particles detected near Saturn by the Voyager plasma wave instrument. Icarus **53**, 236–254 (1983). https://doi.org/10.1016/0019-1035(83)90145-8

D.A. Gurnett, T.F. Averkamp, F.L. Scarf, E. Grun, Dust particles detected near Giacobini-Zinner by the ICE plasma wave instrument. Geophys. Res. Lett. **13**, 291–294 (1986). https://doi.org/10.1029/GL013i003p00291

D.A. Gurnett, W.S. Kurth, K.L. Scarf, J.A. Burns, J.N. Cuzzi, Micron-sized particle impacts detected near Uranus by the Voyager 2 plasma wave instrument. J. Geophys. Res. **92**(14), 14959–14968 (1987). https://doi.org/10.1029/JA092iA13p14959

D.A. Gurnett, W.S. Kurth, L.J. Granroth, S.C. Allendorf, R.L. Poynter, Micron-sized particles detected near Neptune by the Voyager 2 plasma wave instrument. J. Geophys. Res. **96**, 19 (1991). https://doi.org/10.1029/91JA01270

D.A. Gurnett, W.S. Kurth, D.L. Kirchner, G.B. Hospodarsky, T.F. Averkamp, P. Zarka, A. Lecacheux, R. Manning, A. Roux, P. Canu, N. Cornilleau-Wehrlin, P. Galopeau, A. Meyer,hajdukova:2018iaubook A. Meyer, R. Boström, G. Gustafsson, J.E. Wahlund, L. Åhlen, H.O. Rucker, H.P. Ladreiter, W. Macher, L.J.C. Woolliscroft, H. Alleyne, M.L. Kaiser, M.D. Desch, W.M. Farrell, C.C. Harvey, P. Louarn, P.J. Kellogg, K. Goetz, A. Pedersen, The Cassini radio and plasma wave investigation. Space Sci. Rev. **114**, 395–463 (2004). https://doi.org/10.1007/s11214-004-1434-0

B.A.S. Gustafson, Physics of zodiacal dust. Annu. Rev. Earth Planet. Sci. **22**, 553–595 (1994). https://doi.org/10.1146/annurev.ea.22.050194.003005

B.S. Gustafson, N. Misconi, Streaming of interstellar grains in the solar system. Nature **282**, 276–278 (1979)

M. Hajdukova, V.J. Sterken, P. Wiegert, Interstellar meteoroids (2019)

J.K. Hillier, S.F. Green, N. McBride, J.P. Schwanethal, F. Postberg, R. Srama, S. Kempf, G. Moragas-Klostermeyer, J.A.M. McDonnell, E. Grün, The composition of Saturn's E ring. Mon. Not. R. Astron. Soc. **377**, 1588–1596 (2007). https://doi.org/10.1111/j.1365-2966.2007.11710.x

M. Horanyi, Charged dust dynamics in the solar system. Annu. Rev. Astron. Astrophys. **34**, 383–418 (1996). https://doi.org/10.1146/annurev.astro.34.1.383

ISPE, Meteorit. Planet. Sci. **49**(9), 1509–1733 (2014). http://onlinelibrary.wiley.com/doi/10.1111/maps.2014.49.issue-9/issuetoc

E.B. Jenkins, A unified representation of gas-phase element depletions in the interstellar medium. Astrophys. J. **700**, 1299–1348 (2009). https://doi.org/10.1088/0004-637X/700/2/1299

L.P. Keller, S. Messenger, On the origins of GEMS grains. Geochim. Cosmochim. Acta **75**, 5336–5365 (2011). https://doi.org/10.1016/j.gca.2011.06.040

P.J. Kellogg, K. Goetz, S.J. Monson, Dust impact signals on the wind spacecraft. J. Geophys. Res. Space Phys. **121**, 966–991 (2016). https://doi.org/10.1002/2015JA021124

F. Kemper, W.J. Vriend, A.G.G.M. Tielens, The absence of crystalline silicates in the diffuse interstellar medium. Astrophys. J. **609**, 826–837 (2004). https://doi.org/10.1086/421339. astro-ph/0403609

S. Kempf, R. Srama, N. Altobelli, S. Auer, V. Tschernjawski, J. Bradley, M.E. Burton, S. Helfert, T.V. Johnson, H. Krüger, G. Moragas-Klostermeyer, E. Grün, Cassini between Earth and asteroid belt: first in-situ charge measurements of interplanetary grains. Icarus **171**, 317–335 (2004). https://doi.org/10.1016/j.icarus.2004.05.017

S. Kempf, N. Altobelli, C. Briois, E. Grün, M. Horanyi, F. Postberg, J. Schmidt, R. Srama, Z. Sternovsky, G. Tobie, M. Zolotov, SUDA: a dust mass spectrometer for compositional surface mapping for a mission to Europa, in *European Planetary Science Congress*, vol. 9 (2014), EPSC2014-229

H. Kimura, Interstellar dust in the Local Cloud surrounding the Sun. Mon. Not. R. Astron. Soc. **449**, 2250–2258 (2015). https://doi.org/10.1093/mnras/stv427

H. Kimura, On the photoelectric quantum yield of small dust particles. Mon. Not. R. Astron. Soc. **459**, 2751–2761 (2016). https://doi.org/10.1093/mnras/stw820. 1604.03664

H. Kimura, High radiation pressure on interstellar dust computed by light-scattering simulation on fluffy agglomerates of magnesium-silicate grains with metallic-iron inclusions. Astrophys. J. Lett. **839**, L23 (2017). https://doi.org/10.3847/2041-8213/aa6c2d. 1704.02066

H. Kimura, I. Mann, The electric charging of interstellar dust in the solar system and consequences for its dynamics. Astrophys. J. **499**, 454–462 (1998). https://doi.org/10.1086/305613

H. Kimura, I. Mann, Filtering of the interstellar dust flow near the heliopause: the importance of secondary electron emission for the grain charging. Earth Planets Space **51**, 1223–1232 (1999). https://doi.org/10.1186/BF03351596

H. Kimura, I. Mann, Selection effects on interstellar dust in heliosphere. Adv. Space Res. **25**, 299–302 (2000). https://doi.org/10.1016/S0273-1177(99)00952-7

H. Kimura, I. Mann, E.K. Jessberger, Composition, structure, and size distribution of dust in the local interstellar cloud. Astrophys. J. **583**, 314–321 (2003a). https://doi.org/10.1086/345102

H. Kimura, I. Mann, E.K. Jessberger, Elemental abundances and mass densities of dust and gas in the local interstellar cloud. Astrophys. J. **582**, 846–858 (2003b). https://doi.org/10.1086/344691

D. Koschny, R.H. Soja, C. Engrand, G.J. Flynn, J. Lasue, A.C. Levasseur-Regourd, T. Nakamura, D. Malaspina, A.R. Poppe, V.J. Sterken, J.M. Trigo-Rodríguez, Interplanetary dust, meteoroids, meteors and meteorites. Space Sci. Rev. **215**(4), 1–62 (2019)

H. Krüger, M. Landgraf, N. Altobelli, E. Grün, Interstellar dust in the solar system. Space Sci. Rev. **130**, 401–408 (2007). https://doi.org/10.1007/s11214-007-9181-7. 0706.3110

H. Krüger, P. Strub, E. Grün, V.J. Sterken, Sixteen years of Ulysses interstellar dust measurements in the solar system. I. Mass distribution and gas-to-dust mass ratio. Astrophys. J. **812**, 139 (2015). https://doi.org/10.1088/0004-637X/812/2/139. 1510.06180

H. Krüger, M. Kobayashi, T. Arai, R. Srama, B.V. Sarli, H. Kimura, G. Moragas-Klostermeyer, R. Soja, N. Altobelli, E. Grün, Dust analysis on board the Destiny+ mission to 3200 Phaethon, in *European Planetary Science Congress*, vol. 11 (2017), EPSC2017-204

H. Krüger, N. Altobelli, P. Strub, V. Sterken, R. Srama, E. Grün, Interstellar dust in the inner solar system: model versus in-situ spacecraft data. Astron. Astrophys. **626**, A37 (2019a)

H. Krüger, P. Strub, R. Srama, M. Kobayashi, T. Arai, H. Kimura, T. Hirai, G. Moragas-Klostermeyer, N. Altobelli, V. Sterken, J. Agarwal, E. Grün, Modelling DESTINY+ interplanetary and interstellar dust measurements en route to the active asteroid (3200) Phaethon. Planet. Space Sci. **172**, 22–42 (2019b)

W.S. Kurth, T.F. Averkamp, D.A. Gurnett, Z. Wang, Cassini RPWS observations of dust in Saturn's E ring. Planet. Space Sci. **54**, 988–998 (2006). https://doi.org/10.1016/j.pss.2006.05.011

H. Laakso, R. Grard, A. Pedersen, G. Schwehm, Impacts of large dust particles on the VEGA spacecraft. Adv. Space Res. **9**, 269–272 (1989). https://doi.org/10.1016/0273-1177(89)90273-1

M. Landgraf, PhD thesis. Ruprecht-Karls-Univ, Heidelberg (1998)

M. Landgraf, Modeling the motion and distribution of interstellar dust inside the heliosphere. J. Geophys. Res. **105**(10), 10303–10316 (2000)

M. Landgraf, K. Augustsson, E. Grün, B.A.S. Gustafson, Deflection of the local interstellar dust flow by solar radiation pressure. Science **286**, 2319–2322 (1999a)

M. Landgraf, M. Müller, E. Grün, Prediction of the in-situ dust measurements of the stardust mission to comet 81P/Wild 2. Planet. Space Sci. **47**, 1029–1050 (1999b). https://doi.org/10.1016/S0032-0633(99)00031-8. astro-ph/9904204

M. Landgraf, W.J. Baggaley, E. Grün, H. Krüger, G. Linkert, Aspects of the mass distribution of interstellar dust grains in the solar system from in situ measurements. J. Geophys. Res. **105**(10), 10343–10352 (2000)

M. Landgraf, H. Krüger, N. Altobelli, E. Grün, Penetration of the heliosphere by the interstellar dust stream during solar maximum. J. Geophys. Res. Space Phys. **108**, 8030 (2003). https://doi.org/10.1029/2003JA009872

J. Leitner, C. Vollmer, P. Hoppe, J. Zipfel, Characterization of presolar material in the CR chondrite Northwest Africa 852. Astrophys. J. **745**, 38 (2012). https://doi.org/10.1088/0004-637X/745/1/38

A.C. Levasseur-Regourd, J. Agarwal, H. Cottin, C. Engrand, G. Flynn, M. Fulle, T. Gombosi, Y. Langevin, J. Lasue, T. Mannel, S. Merouane, O. Poch, N. Thomas, A. Westphal, Cometary dust. Space Sci. Rev. **214**(3), 64 (2018). https://doi.org/10.1007/s11214-018-0496-3

E.H. Levy, J.R. Jokipii, Penetration of interstellar dust into the Solar System. Nature **264**, 423–424 (1976)

T.J. Linde, T.I. Gombosi, Interstellar dust filtration at the heliospheric interface. J. Geophys. Res. **105**(10), 10411–10418 (2000). https://doi.org/10.1029/1999JA900149

Q. Ma, L.S. Matthews, V. Land, T.W. Hyde, Charging of aggregate grains in astrophysical environments. Astrophys. J. **763**, 77 (2013). https://doi.org/10.1088/0004-637X/763/2/77. 1210.0459

D. Malaspina, Coordinated Data Analysis Web: The Wind ISD Database (2017). wi_l3-dustimpact_waves. https://cdaweb.sci.gsfc.nasa.gov/index.html/

D.M. Malaspina, L.B. Wilson, A database of interplanetary and interstellar dust detected by the Wind spacecraft. J. Geophys. Res. Space Phys. **121**, 9369–9377 (2016). https://doi.org/10.1002/2016JA023209
D.M. Malaspina, M. Horányi, A. Zaslavsky, K. Goetz, L.B. Wilson, K. Kersten, Interplanetary and interstellar dust observed by the Wind/WAVES electric field instrument. Geophys. Res. Lett. **41**, 266–272 (2014). https://doi.org/10.1002/2013GL058786
M. Masanori, R. Srama, H. Krüger, T. Arai, H. Kimura, DESTINY+ Dust Analyzer, in *49th Lunar and Planetary Science Conference 2018* (2018) (LPI Contrib. No. 2083)
J.S. Mathis, W. Rumpl, K.H. Nordsieck, The size distribution of interstellar grains. Astrophys. J. **217**, 425–433 (1977). https://doi.org/10.1086/155591
N. McBride, M. Jam, Meteoroid impacts on spacecraft: sporadics, streams, and the 1999 Leonids. Planet. Space Sci. **47**, 1005–1013 (1999). https://doi.org/10.1016/S0032-0633(99)00023-9
D.J. McComas, M. Bzowski, P. Frisch, S.A. Fuselier, M.A. Kubiak, H. Kucharek, T. Leonard, E. Möbius, N.A. Schwadron, J.M. Sokół, P. Swaczyna, M. Witte, Warmer local interstellar medium: a possible resolution of the Ulysses-IBEX enigma. Astrophys. J. **801**, 28 (2015). https://doi.org/10.1088/0004-637X/801/1/28
K.J. Meech, R. Weryk, M. Micheli, J.T. Kleyna, O.R. Hainaut, R. Jedicke, R.J. Wainscoat, K.C. Chambers, J.V. Keane, A. Petric, L. Denneau, E. Magnier, T. Berger, M.E. Huber, H. Flewelling, C. Waters, E. Schunova-Lilly, S. Chastel, A brief visit from a red and extremely elongated interstellar asteroid. Nature **552**, 378–381 (2017). https://doi.org/10.1038/nature25020
N. Meyer-Vernet, M.G. Aubier, B.M. Pedersen, Voyager 2 at Uranus—grain impacts in the ring plane. Geophys. Res. Lett. **13**, 617–620 (1986). https://doi.org/10.1029/GL013i007p00617
N. Meyer-Vernet, A. Lecacheux, M.L. Kaiser, D.A. Gurnett, Detecting nanoparticles at radio frequencies: Jovian dust stream impacts on Cassini/RPWS. Geophys. Res. Lett. **36**, L03103 (2009a). https://doi.org/10.1029/2008GL036752
N. Meyer-Vernet, M. Maksimovic, A. Czechowski, I. Mann, I. Zouganelis, K. Goetz, M.L. Kaiser, O.C. St. Cyr, J.L. Bougeret, S.D. Bale, Dust detection by the Wave Instrument on STEREO: nanoparticles picked up by the solar wind? Sol. Phys. **256**, 463 (2009b)
G.E. Morfill, E. Gruen, The motion of charged dust particles in interplanetary space. I—The zodiacal dust cloud. II—Interstellar grains. Planet. Space Sci. **27**, 1269–1292 (1979). https://doi.org/10.1016/0032-0633(79)90105-3
T. Mukai, On the charge distribution of interplanetary grains. Astron. Astrophys. **99**, 1–6 (1981)
F.M. Neubauer, K.H. Glassmeier, A.J. Coates, R. Goldstein, M.H. Acuna, Hypervelocity dust particle impacts observed by the Giotto magnetometer and plasma experiments. Geophys. Res. Lett. **17**, 1809–1812 (1990). https://doi.org/10.1029/GL017i011p01809
P. Oberc, Electric antenna as a dust detector. Adv. Space Res. **17**, 105–110 (1996). https://doi.org/10.1016/0273-1177(95)00766-8
A. Pais, *Inward Bound: Of Matter and Forces in the Physical World* (Oxford University Press, London, 1986)
F. Pantellini, S. Belheouane, N. Meyer-Vernet, A. Zaslavsky, Nano dust impacts on spacecraft and boom antenna charging. Astrophys. Space Sci. **341**, 309–314 (2012). https://doi.org/10.1007/s10509-012-1108-4. 1205.1430
E.N. Parker, Dynamics of the interplanetary gas and magnetic fields. Astrophys. J. **128**, 664 (1958). https://doi.org/10.1086/146579
B.M. Pedersen, N. Meyer-Vernet, M.G. Aubier, P. Zarka, Dust distribution around Neptune—grain impacts near the ring plane measured by the Voyager planetary radio astronomy experiment. J. Geophys. Res. **96**, 19 (1991). https://doi.org/10.1029/91JA01601
F. Postberg, S. Kempf, J.K. Hillier, R. Srama, S.F. Green, N. McBride, E. Grün, The E-ring in the vicinity of Enceladus. II. Probing the moon's interior—the composition of E-ring particles. Icarus **193**, 438–454 (2008). https://doi.org/10.1016/j.icarus.2007.09.001
F. Postberg, S. Kempf, D. Rost, T. Stephan, R. Srama, M. Trieloff, A. Mocker, M. Goerlich, Discriminating contamination from particle components in spectra of Cassini's dust detector CDA. Planet. Space Sci. **57**, 1359–1374 (2009a). https://doi.org/10.1016/j.pss.2009.06.027
F. Postberg, S. Kempf, J. Schmidt, N. Brilliantov, A. Beinsen, B. Abel, U. Buck, R. Srama, Sodium salts in E-ring ice grains from an ocean below the surface of Enceladus. Nature **459**, 1098–1101 (2009b). https://doi.org/10.1038/nature08046
F. Postberg, J.K. Hillier, S.P. Armes, S. Bugiel, A. Butterworth, D. Dupin, L.A. Fielding, S. Fujii, Z. Gainsforth, E. Grün, Y.W. Li, R. Srama, V. Sterken, J. Stodolna, M. Trieloff, A. Westphal, C. Achilles, C. Allen, A. Ansari, S. Bajt, N. Bassim, R.K. Bastien, H.A. Bechtel, J. Borg, F. Brenker, J. Bridges, D.E. Brownlee, M. Burchell, M. Burghammer, H. Changela, P. Cloetens, A. Davis, R. Doll, C. Floss, G. Flynn, D. Frank, P.R. Heck, P. Hoppe, G. Huss, J. Huth, A. Kearsley, A.J. King, B. Lai, J. Leitner, L. Lemelle, A. Leonard, H. Leroux, R. Lettieri, W. Marchant, L.R. Nittler, R. Ogliore, W.J. Ong, M.C. Price, S.A. Sandford, J.A.S. Tressaras, S. Schmitz, T. Schoonjans, K. Schreiber, G. Silversmit, A.

Simionovici, V.A. Solé, F. Stadermann, T. Stephan, R.M. Stroud, S. Sutton, P. Tsou, A. Tsuchiyama, T. Tyliczszak, B. Vekemans, L. Vincze, D. Zevin, M.E. Zolensky, Stardust Interstellar Preliminary Examination IX: high-speed interstellar dust analog capture in Stardust flight-spare aerogel. Meteorit. Planet. Sci. **49**, 1666–1679 (2014). https://doi.org/10.1111/maps.12173

S. Redfield, J.L. Linsky, The three-dimensional structure of the warm local interstellar medium. II. The Colorado model of the local interstellar cloud. Astrophys. J. **534**, 825–837 (2000). https://doi.org/10.1086/308769

S. Redfield, B.E. Wood, J.L. Linsky, Physical structure of the local interstellar medium. Adv. Space Res. **34**, 41–45 (2004). https://doi.org/10.1016/j.asr.2003.02.053

M. Rowan-Robinson, B. May, An improved model for the infrared emission from the zodiacal dust cloud: cometary, asteroidal and interstellar dust. Mon. Not. R. Astron. Soc. **429**, 2894–2902 (2013). https://doi.org/10.1093/mnras/sts471. 1212.4759

F.L. Scarf, D.A. Gurnett, W.S. Kurth, R.L. Poynter, Voyager 2 plasma wave observations at Saturn. Science **215**, 587–594 (1982). https://doi.org/10.1126/science.215.4532.587

N.A. Schwadron, E. Möbius, T. Leonard, S.A. Fuselier, D.J. McComas, D. Heirtzler, H. Kucharek, F. Rahmanifard, M. Bzowski, M.A. Kubiak, J.M. Sokół, P. Swaczyna, P. Frisch, Determination of interstellar He parameters using five years of data from the IBEX: beyond closed form approximations. Astrophys. J. Suppl. Ser. **220**, 25 (2015). https://doi.org/10.1088/0067-0049/220/2/25

G. Schwehm, Radiation pressure on interplanetary dust particles, in *Interplanetary Dust and Zodiacal Light*, ed. by H. Elsaesser, H. Fechtig. Lecture Notes in Physics, vol. 48 (Springer, Berlin, 1976), pp. 459–463. https://doi.org/10.1007/3-540-07615-8_526

K. Silsbee, B.T. Draine, Radiation pressure on fluffy submicron-sized grains. Astrophys. J. **818**, 133 (2016). https://doi.org/10.3847/0004-637X/818/2/133. 1508.00646

A.S. Simionovici, L. Lemelle, P. Cloetens, V.A. Solé, J.A.S. Tresseras, A.L. Butterworth, A.J. Westphal, Z. Gainsforth, J. Stodolna, C. Allen, D. Anderson, A. Ansari, S. Bajt, N. Bassim, R.K. Bastien, H.A. Bechtel, J. Borg, F.E. Brenker, J. Bridges, D.E. Brownlee, M. Burchell, M. Burghammer, H. Changela, A.M. Davis, R. Doll, C. Floss, G. Flynn, D.R. Frank, E. Grün, P.R. Heck, J.K. Hillier, P. Hoppe, B. Hudson, J. Huth, B. Hvide, A. Kearsley, A.J. King, B. Lai, J. Leitner, A. Leonard, H. Leroux, R. Lettieri, W. Marchant, L.R. Nittler, R. Ogliore, W.J. Ong, F. Postberg, M.C. Price, S.A. Sandford, S. Schmitz, T. Schoonjans, G. Silversmit, R. Srama, F.J. Stadermann, T. Stephan, V.J. Sterken, R.M. Stroud, S. Sutton, M. Trieloff, P. Tsou, A. Tsuchiyama, T. Tyliszczak, B. Vekemans, L. Vincze, J. Korff, N. Wordsworth, D. Zevin, M.E. Zolensky, Stardust Interstellar Preliminary Examination VI: quantitative elemental analysis by synchrotron X-ray fluorescence nanoimaging of eight impact features in aerogel. Meteorit. Planet. Sci. **49**, 1612–1625 (2014). https://doi.org/10.1111/maps.12208

J.D. Slavin, P.C. Frisch, The boundary conditions of the heliosphere: photoionization models constrained by interstellar and in situ data. Astron. Astrophys. **491**, 53–68 (2008). https://doi.org/10.1051/0004-6361:20078101

J.D. Slavin, P.C. Frisch, H.R. Müller, J. Heerikhuisen, N.V. Pogorelov, W.T. Reach, G. Zank, Trajectories and distribution of interstellar dust grains in the heliosphere. Astrophys. J. **760**, 46 (2012). https://doi.org/10.1088/0004-637X/760/1/46. 1210.1127

R. Srama, T.J. Ahrens, N. Altobelli, S. Auer, J.G. Bradley, M. Burton, V.V. Dikarev, T. Economou, H. Fechtig, M. Görlich, M. Grande, A. Graps, E. Grün, O. Havnes, S. Helfert, M. Horanyi, E. Igenbergs, E.K. Jessberger, T.V. Johnson, S. Kempf, A.V. Krivov, H. Krüger, A. Mocker-Ahlreep, G. Moragas-Klostermeyer, P. Lamy, M. Landgraf, D. Linkert, G. Linkert, F. Lura, J.A.M. McDonnell, D. Möhlmann, G.E. Morfill, M. Müller, M. Roy, G. Schäfer, G. Schlotzhauer, G.H. Schwehm, F. Spahn, M. Stübig, J. Svestka, V. Tschernjawski, A.J. Tuzzolino, R. Wäsch, H.A. Zook, The Cassini cosmic dust analyzer. Space Sci. Rev. **114**, 465–518 (2004). https://doi.org/10.1007/s11214-004-1435-z

R. Srama, T. Stephan, E. Grün, N. Pailer, A. Kearsley, A. Graps, R. Laufer, P. Ehrenfreund, N. Altobelli, K. Altwegg, S. Auer, J. Baggaley, M.J. Burchell, J. Carpenter, L. Colangeli, F. Esposito, S.F. Green, H. Henkel, M. Horanyi, A. Jäckel, S. Kempf, N. McBride, G. Moragas-Klostermeyer, H. Krüger, P. Palumbo, A. Srowig, M. Trieloff, P. Tsou, Z. Sternovsky, O. Zeile, H.P. Röser, Sample return of interstellar matter (SARIM). Exp. Astron. **23**, 303–328 (2009). https://doi.org/10.1007/s10686-008-9088-7

R. Srama, E. Gruün, A. Krivov, R. Soja, V. Sterken, Z. Sternovsky, S2d2: solar system debris disk (2013). http://www.irs.uni-stuttgart.de/cosmicdust/missions/debrisdisk/

O.C. St. Cyr, M.L. Kaiser, N. Meyer-Vernet, R.A. Howard, R.A. Harrison, S.D. Bale, W.T. Thompson, K. Goetz, M. Maksimovic, J.L. Bougeret, D. Wang, S. Crothers, STEREO SECCHI and S/WAVES observations of spacecraft debris caused by micron-size interplanetary dust impacts. Sol. Phys. **256**, 475–488 (2009). https://doi.org/10.1007/s11207-009-9362-5

V.J. Sterken, N. Altobelli, S. Kempf, G. Schwehm, R. Srama, E. Grün, The flow of interstellar dust into the solar system. Astron. Astrophys. **538**, A102 (2012). https://doi.org/10.1051/0004-6361/201117119

V.J. Sterken, N. Altobelli, S. Kempf, H. Krüger, R. Srama, P. Strub, E. Grün, The filtering of interstellar dust in the solar system. Astron. Astrophys. **552**, A130 (2013). https://doi.org/10.1051/0004-6361/201219609

V.J. Sterken, A.J. Westphal, N. Altobelli, E. Grün, J.K. Hillier, F. Postberg, R. Srama, C. Allen, D. Anderson, A. Ansari, S. Bajt, R.S. Bastien, N. Bassim, H.A. Bechtel, J. Borg, F.E. Brenker, J. Bridges, D.E. Brownlee, M. Burchell, M. Burghammer, A.L. Butterworth, H. Changela, P. Cloetens, A.M. Davis, R. Doll, C. Floss, G. Flynn, D. Frank, Z. Gainsforth, P.R. Heck, P. Hoppe, B. Hudson, J. Huth, B. Hvide, A. Kearsley, A.J. King, B. Lai, J. Leitner, L. Lemelle, H. Leroux, A. Leonard, R. Lettieri, W. Marchant, L.R. Nittler, R. Ogliore, W.J. Ong, M.C. Price, S.A. Sandford, J.A.S. Tresseras, S. Schmitz, T. Schoonjans, G. Silversmit, A. Simionovici, V.A. Solé, T. Stephan, J. Stodolna, R.M. Stroud, S. Sutton, M. Trieloff, P. Tsou, A. Tsuchiyama, T. Tyliszczak, B. Vekemans, L. Vincze, J. von Korff, N. Wordsworth, D. Zevin, M.E. Zolensky, Stardust Interstellar Preliminary Examination X: impact speeds and directions of interstellar grains on the Stardust dust collector. Meteorit. Planet. Sci. **49**, 1680–1697 (2014). https://doi.org/10.1111/maps.12219

V.J. Sterken, P. Strub, H. Krüger, R. von Steiger, P. Frisch, Sixteen years of Ulysses interstellar dust measurements in the solar system. III. Simulations and data unveil new insights into local interstellar dust. Astrophys. J. **812**, 141 (2015). https://doi.org/10.1088/0004-637X/812/2/141

V. Sterken, G. Moragas-Klostermeyer, J. Hillier, L. Fielding, J. Lovett, S. Armes, N. Fechler, R. Srama, S. Bugiel, K. Hornung, Impact ionization experiments with porous cosmic dust particle analogs, in *EGU General Assembly Conference Abstracts, EGU General Assembly Conference Abstracts*, vol. 18 (2016), EPSC2016-16018

R.M. Stroud, C. Allen, A. Ansari, D. Anderson, S. Bajt, N. Bassim, R.S. Bastien, H.A. Bechtel, J. Borg, F.E. Brenker, J. Bridges, D.E. Brownlee, M. Burchell, M. Burghammer, A.L. Butterworth, H. Changela, P. Cloetens, A.M. Davis, R. Doll, C. Floss, G. Flynn, D.R. Frank, Z. Gainsforth, E. Grün, P.R. Heck, J.K. Hillier, P. Hoppe, J. Huth, B. Hvide, A. Kearsley, A.J. King, P. Kotula, B. Lai, J. Leitner, L. Lemelle, H. Leroux, A. Leonard, R. Lettieri, W. Marchant, L.R. Nittler, R. Ogliore, W.J. Ong, F. Postberg, M.C. Price, S.A. Sandford, J.A.S. Tresseras, S. Schmitz, T. Schoonjans, K. Schreiber, G. Silversmit, A.S. Simionovici, V.A. Solé, R. Srama, T. Stephan, V.J. Sterken, J. Stodolna, S. Sutton, M. Trieloff, P. Tsou, A. Tsuchiyama, T. Tyliszczak, B. Vekemans, L. Vincze, A.J. Westphal, J. von Korff, D. Zevin, M.E. Zolensky, Stardust Interstellar Preliminary Examination XI: identification and elemental analysis of impact craters on Al foils from the Stardust Interstellar Dust Collector. Meteorit. Planet. Sci. **49**, 1698–1719 (2014). https://doi.org/10.1111/maps.12136

P. Strub, V.J. Sterken, H. Krüger, E. Grün, M. Horanyi, Interstellar dust flow through the solar system, in *American Institute of Physics Conference Series*, ed. by V.Y. Nosenko, P.K. Shukla, M.H. Thoma, H.M. Thomas. American Institute of Physics Conference Series, vol. 1397 (2011), pp. 385–386. https://doi.org/10.1063/1.3659855

P. Strub, H. Krüger, V.J. Sterken, Sixteen years of Ulysses interstellar dust measurements in the solar system. II. Fluctuations in the dust flow from the data. Astrophys. J. **812**, 140 (2015). https://doi.org/10.1088/0004-637X/812/2/140. 1508.03242

P. Strub, V.J. Sterken, R. Soja, H. Krüger, E. Grün, R. Srama, Heliospheric modulation of the interstellar dust flow on to Earth. Astron. Astrophys. **621**, A54 (2019). https://doi.org/10.1051/0004-6361/201832644

F.M. Thayer, D.M. Malaspina, A. Collette, Z. Sternovsky, Variation in relative dust impact charge recollection with antenna to spacecraft potential on STEREO. J. Geophys. Res. Space Phys. **121**, 4998–5004 (2016). https://doi.org/10.1002/2015JA021983

J.I. Thorpe, C. Parvini, J.M. Trigo-Rodríguez, Detection and measurement of micrometeoroids with LISA Pathfinder. Astron. Astrophys. **586**, A107 (2016). https://doi.org/10.1051/0004-6361/201527658

J.I. Thorpe, T.B. Littenberg, J. Baker, J. Slutsky (The LISA Pathfinder Team) LISA Pathfinder as a micrometeoroid instrument. J. Phys. Conf. Ser. **840**, 012007 (2017). https://doi.org/10.1088/1742-6596/840/1/012007

D. Tsintikidis, D.A. Gurnett, W.S. Kurth, L.J. Granroth, Micron-sized particles detected in the vicinity of Jupiter by the Voyager plasma wave instruments. Geophys. Res. Lett. **23**, 997–1000 (1996). https://doi.org/10.1029/96GL00961

B.T. Tsurutani, D.R. Clay, L.D. Zhang, B. Dasgupta, D. Brinza, M. Henry, A. Mendis, S. Moses, K.H. Glassmeier, G. Musmann, I. Richter, Dust impacts at comet P/Borrelly. Geophys. Res. Lett. **30**, 2134 (2003). https://doi.org/10.1029/2003GL017580

M.K. Wallis, Penetration of charged interstellar dust into the solar system. Mon. Not. R. Astron. Soc. **227**, 331–339 (1987). https://doi.org/10.1093/mnras/227.2.331

S. Wang, A. Li, B.W. Jiang, Very large interstellar grains as evidenced by the mid-infrared extinction. Astrophys. J. **811**, 38 (2015). https://doi.org/10.1088/0004-637X/811/1/38. 1508.03403

J.C. Weingartner, B.T. Draine, Dust grain-size distributions and extinction in the Milky Way, Large Magellanic Cloud, and Small Magellanic Cloud. Astrophys. J. **548**, 296–309 (2001). https://doi.org/10.1086/318651. astro-ph/0008146

A.J. Westphal, D. Anderson, A.L. Butterworth, D.R. Frank, R. Lettieri, W. Marchant, J. von Korff, D. Zevin, A. Ardizzone, A. Campanile, M. Capraro, K. Courtney, M.N. Criswell, D. Crumpler, R. Cwik, F.J. Gray, B. Hudson, G. Imada, J. Karr, L.L.W. Wah, M. Mazzucato, P.G. Motta, C. Rigamonti, R.C. Spencer, S.B. Woodrough, I.C. Santoni, G. Sperry, J.N. Terry, N. Wordsworth, T. Yahnke, C. Allen, A. Ansari, S. Bajt, R.K. Bastien, N. Bassim, H.A. Bechtel, J. Borg, F.E. Brenker, J. Bridges, D.E. Brownlee, M. Burchell, M. Burghammer, H. Changela, P. Cloetens, A.M. Davis, R. Doll, C. Floss, G. Flynn, Z. Gainsforth, E. Grün, P.R. Heck, J.K. Hillier, P. Hoppe, J. Huth, B. Hvide, A. Kearsley, A.J. King, B. Lai, J. Leitner, L. Lemelle, H. Leroux, A. Leonard, L.R. Nittler, R. Ogliore, W.J. Ong, F. Postberg, M.C. Price, S.A. Sandford, J.A.S. Tresseras, S. Schmitz, T. Schoonjans, G. Silversmit, A.S. Simionovici, V.A. Solé, R. Srama, T. Stephan, V.J. Sterken, J. Stodolna, R.M. Stroud, S. Sutton, M. Trieloff, P. Tsou, A. Tsuchiyama, T. Tyliszczak, B. Vekemans, L. Vincze, M.E. Zolensky, Stardust interstellar preliminary examination I: identification of tracks in aerogel. Meteorit. Planet. Sci. **49**, 1509–1521 (2014a). https://doi.org/10.1111/maps.12168

A.J. Westphal, H.A. Bechtel, F.E. Brenker, A.L. Butterworth, G. Flynn, D.R. Frank, Z. Gainsforth, J.K. Hillier, F. Postberg, A.S. Simionovici, V.J. Sterken, R.M. Stroud, C. Allen, D. Anderson, A. Ansari, S. Bajt, R.K. Bastien, N. Bassim, J. Borg, J. Bridges, D.E. Brownlee, M. Burchell, M. Burghammer, H. Changela, P. Cloetens, A.M. Davis, R. Doll, C. Floss, E. Grün, P.R. Heck, P. Hoppe, B. Hudson, J. Huth, B. Hvide, A. Kearsley, A.J. King, B. Lai, J. Leitner, L. Lemelle, H. Leroux, A. Leonard, R. Lettieri, W. Marchant, L.R. Nittler, R. Ogliore, W.J. Ong, M.C. Price, S.A. Sandford, J.A.S. Tresseras, S. Schmitz, T. Schoonjans, G. Silversmit, V.A. Solé, R. Srama, F. Stadermann, T. Stephan, J. Stodolna, S. Sutton, M. Trieloff, P. Tsou, A. Tsuchiyama, T. Tyliszczak, B. Vekemans, L. Vincze, J. Korff, N. Wordsworth, D. Zevin, M.E. Zolensky, Final reports of the Stardust Interstellar Preliminary Examination. Meteorit. Planet. Sci. **49**, 1720–1733 (2014b). https://doi.org/10.1111/maps.12221

A.J. Westphal, R.M. Stroud, H.A. Bechtel, F.E. Brenker, A.L. Butterworth, G.J. Flynn, D.R. Frank, Z. Gainsforth, J.K. Hillier, F. Postberg, A.S. Simionovici, V.J. Sterken, L.R. Nittler, C. Allen, D. Anderson, A. Ansari, S. Bajt, R.K. Bastien, N. Bassim, J. Bridges, D.E. Brownlee, M. Burchell, M. Burghammer, H. Changela, P. Cloetens, A.M. Davis, R. Doll, C. Floss, E. Grün, P.R. Heck, P. Hoppe, B. Hudson, J. Huth, A. Kearsley, A.J. King, B. Lai, J. Leitner, L. Lemelle, A. Leonard, H. Leroux, R. Lettieri, W. Marchant, R. Ogliore, W.J. Ong, M.C. Price, S.A. Sandford, J.A.S. Tresseras, S. Schmitz, T. Schoonjans, K. Schreiber, G. Silversmit, V.A. Solé, R. Srama, F. Stadermann, T. Stephan, J. Stodolna, S. Sutton, M. Trieloff, P. Tsou, T. Tyliszczak, B. Vekemans, L. Vincze, J. Von Korff, N. Wordsworth, D. Zevin, M.E. Zolensky, Evidence for interstellar origin of seven dust particles collected by the Stardust spacecraft. Science **345**, 786–791 (2014c). https://doi.org/10.1126/science.1252496

M. Witte, Kinetic parameters of interstellar neutral helium. Review of results obtained during one solar cycle with the Ulysses/GAS-instrument. Astron. Astrophys. **426**, 835–844 (2004). https://doi.org/10.1051/0004-6361:20035956

S.R. Wood, D.M. Malaspina, L. Andersson, M. Horanyi, Hypervelocity dust impacts on the Wind spacecraft: correlations between Ulysses and Wind interstellar dust detections. J. Geophys. Res. Space Phys. **120**, 7121–7129 (2015). https://doi.org/10.1002/2015JA021463

S.Y. Ye, W.S. Kurth, G.B. Hospodarsky, T.F. Averkamp, D.A. Gurnett, Dust detection in space using the monopole and dipole electric field antennas. J. Geophys. Res. Space Phys. **121**, 11 (2016). https://doi.org/10.1002/2016JA023266

A. Zaslavsky, Floating potential perturbations due to micrometeoroid impacts: theory and application to S/WAVES data. J. Geophys. Res. Space Phys. **120**, 855–867 (2015). https://doi.org/10.1002/2014JA020635

A. Zaslavsky, N. Meyer-Vernet, I. Mann, A. Czechowski, K. Issautier, G. Le Chat, F. Pantellini, K. Goetz, M. Maksimovic, S.D. Bale, J.C. Kasper, Interplanetary dust detection by radio antennas: mass calibration and fluxes measured by STEREO/WAVES. J. Geophys. Res. Space Phys. **117**, A05102 (2012). https://doi.org/10.1029/2011JA017480

Q. Zhang, Prospects for backtracing 1I/‘Oumuamua and future interstellar objects. Astrophys. J. Lett. **852**, L13 (2018). https://doi.org/10.3847/2041-8213/aaa2f7. 1712.08059

S. Zhukovska, H.P. Gail, M. Trieloff, Evolution of interstellar dust and stardust in the solar neighbourhood. Astron. Astrophys. **479**, 453–480 (2008). https://doi.org/10.1051/0004-6361:20077789. 0706.1155

E. Zinner, Presolar grains, in *Treatise on Geochemistry, Vol. 1. Meteorites and Cosmochemical Processes*, 2nd edn. (2014), pp. 181–213

E. Zinner, S. Amari, R. Guinness, C. Jennings, A.F. Mertz, A.N. Nguyen, R. Gallino, P. Hoppe, M. Lugaro, L.R. Nittler, R.S. Lewis, NanoSIMS isotopic analysis of small presolar grains: search for Si_3N_4 grains from AGB stars and Al and Ti isotopic compositions of rare presolar SiC grains. Geochim. Cosmochim. Acta **71**, 4786–4813 (2007). https://doi.org/10.1016/j.gca.2007.07.012

V. Zubko, E. Dwek, R.G. Arendt, Interstellar dust models consistent with extinction, emission, and abundance constraints. Astrophys. J. Suppl. Ser. **152**, 211–249 (2004). https://doi.org/10.1086/382351. astro-ph/0312641