The Heliosphere's Interaction with Interstellar Dust

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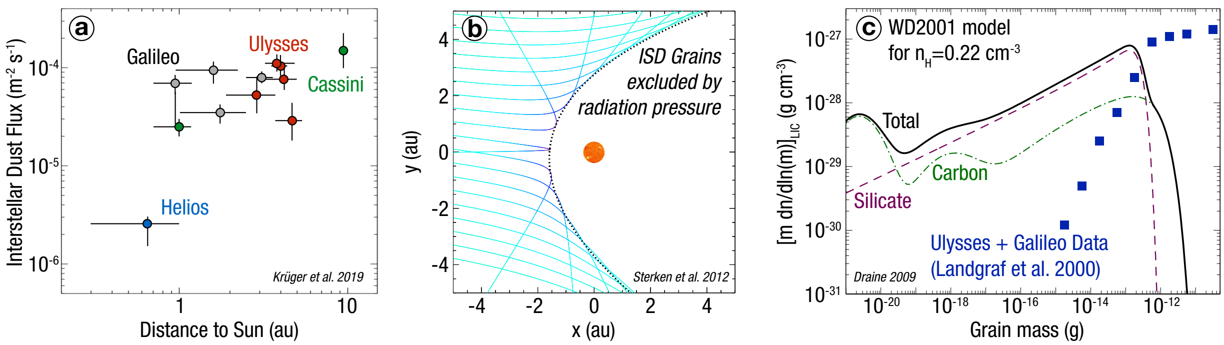

Figure 1. a. ISD flux as a function of heliocentric distance, as detected by multiple missions to date (Krüger *et al.* 2019a). **b.** Representative trajectories showing how the Sun's radiation pressure can exclude ISDs from the inner heliosphere (Sterken *et al.* 2012). **c.** Discrepancy in the distribution of ISD mass between remote-based observations in black (Draine 2009) and in-situ-based observations in blue (Landgraf *et al.* 2000).

Interstellar material in the form of interstellar dust (ISD) grains continuously flows through our heliosphere. Historically, ISD puzzled astronomers only as a nuisance, obscuring or attenuating telescopic observations of stars and creating effects to be removed or corrected for in the analysis and interpretation of optical data. However, in the past several decades, ISD has been recognized to play a critical role in the formation of stars and their planets, as well as the chemistry, dynamics, and energetics of interstellar matter (Draine 2011). The chemical makeup of interstellar gas is complemented by the condensable elements locked in solid macroscopic particles. Surfaces of local ISD particles measured by spacecraft result from heterogenous catalytic chemistry mediated by radiative and collisional charging processes interacting with a surface with unknown chemistry and morphology and processed through interstellar shocks (Frisch et al. 1999). ISD emits and absorbs radiation, acts as sources and sinks of electrons and ions, couples magnetic fields and radiation pressure to the interstellar gas. Understanding the composition and dynamics of ISD enables us to better understand the raw materials present during the formation of the solar system and provides critical context about how the heliosphere interacts with our interstellar neighborhood.

For centuries, our understanding of the interstellar medium was solely based on telescopic observations. A new era opened with the discovery of the flow of ISD through our heliosphere by a dust detector onboard the Ulysses mission during its first encounter with Jupiter in 1992 (Grün *et al.* 1992), and the connection between those dust grains with interstellar gas and dust in the surrounding interstellar medium (Frisch et al. 1999). Figure 1a shows a reanalysis of earlier data from Galileo (Altobelli *et al.* 2005) and Helios (Altobelli *et al.* 2006), and later observations by the Cassini (Altobelli *et al.* 2007) and Ulysses (Krüger *et al.* 2015, 2019a) missions. Additionally, dust observations with antennas from STEREO provided measurements of the dust flux with ecliptic latitude (Belheouane et al. 2012, Zaslavsky et al. 2012), and inferred a dominant ISD size of 100 to 300 nm near 1 au (Zaslavsky et al. 2012, Malaspina et al. 2015).

Multiple spacecraft observed the flow of ISD, leading to an improved understanding of its motion through the heliosphere, shaped by radiation pressure, the Sun's gravity and interaction with the magnetic field (Landgraf *et al.* 2000, Slavin *et al.* 2012). Yet, the mechanisms behind the variability of flux magnitude and direction for the entire data set of 16 years of Ulysses observations remains partially unresolved (Krüger *et al.* 2015, 2019a; Strub *et al.* 2015, 2019; Sterken *et al.* 2012, 2015, 2019). Interpretation of these observations requires comparison to models of the heliosphere and its time variations as well as the characteristics of the Local Interstellar Cloud (LIC) that are not completely determined. Hence, measurements of ISD upstream towards the nose direction and from different locations in the inner heliosphere would bring critical insight to our current understanding of the ISD flow through our heliosphere.

Our heliosphere continuously filters the flow of ISDs, primarily over long timescales through solar radiation pressure and electromagnetic forces on charged grains (e.g. Landgraf *et al.* 2002; Slavin et al. 2012, Sterken *et al.* 2012). At the smallest sizes, the Lorentz force deflects ISD with masses $<10^{-19}$ kg at the heliopause. For small grains that are able to enter the heliosphere, their flux varies considerably (Czechowski and Mann 2003a) as their trajectories are strongly affected by the heliospheric magnetic field, particularly in response to the polarity of the field throughout the solar cycle (Landgraf 2000, Slavin *et al.* 2012). Radiation pressure also prevents an appreciable portion of the flux of the smaller grains from reaching inside 5 au (Fig. 1b), while larger grains are focused by the Sun's gravity.

These effects cause ISD to be filtered by the heliosphere in a size-dependent mechanism that is still not fully understood. Notably, the ISD flowing through the heliosphere has a size distribution that differs markedly from that inferred for pristine ISD in the interstellar medium (Drain et al. 2011). In-situ observations lack small grains and include very large grains that are uncommon in the pristine ISM, as shown in Figure 1c. While the lack of small grains is interpreted to be due to diversion from the inner heliosphere by the heliospheric magnetic field, the excess of large grains remains unresolved. The total elemental abundances, including in the gas phase and in dust, constrain the gas-to-dust mass ratio and in particular places limits on the abundance of large grains since they contain most of the mass. Mapping out the distribution of dust of different sizes within the heliosphere can thus provide key information on ISD and its interaction with the heliosphere that would be difficult to determine otherwise.

The heliosphere's filtration mechanisms are also sensitive to ISD composition via its effects on grain charging and optical properties. Hence the composition of ISD in the inner heliosphere may not be representative of the unperturbed, pristine upstream flow. During two dedicated periods, the Stardust mission collected ISD particles near 1 au and returned them to the ground for laboratory studies (Westphal *et al.* 2014). In addition, the Cassini mission identified and measured the composition of ISD while orbiting Saturn (Altobelli *et al.* 2016). Currently, the remote sensing, laboratory, and in situ observations of ISD are in discord. The seven candidate ISD particles collected by the Stardust mission are diverse in elemental composition, crystal structure, and size, suggesting that individual ISD particles diverge from any one representative model inferred from astronomical observations and theory (Westphal *et al.* 2014). In contrast, Cassini's 36 ISD detections are all Mg-rich grains of silicate and oxide composition with major rock-forming elements (Mg, Si, Fe, Ca) present with only small grain-to-grain variations. Combining direct determination of grain composition with gas phase abundances inferred from absorption line measurements is a powerful technique that is unique to the LIC. Therefore, a definitive determination of the composition of the ISD throughout the heliosphere is an important goal.

NASA's IMAP mission (McComas *et al.* 2018) will make ISD composition measurements near 1 au beginning in 2024, and will significantly add to our current understanding of ISD properties. IMAP will carry the first ISD-dedicated impact ionization time-of-flight dust composition analyzer that will employ state-of-the-art dust detection and compositional analysis methods. IMAP will provide a comprehensive compositional dataset that will allow studies of the heliospheric filtering of ISD grains, albeit only at a one heliocentric distance. Additionally, JAXA's DESTINY+ mission is planned to make ISD observations near 1 au (Krüger et al. 2019b), allowing for the possibility of two-point ISD measurements that could help better separate spatial and temporal variations in ISD flux. However, understanding the ISD flux and directional variability remains an unfinished and challenging task (Frisch et al. 1999; Mann 2010; Slavin et al. 2012; Krüger *et al.* 2015, 2019a, 2019b; Strub *et al.* 2015, 2019; Sterken *et al.* 2015, 2019), given that the majority of ISD observations are very near to the Sun, where large perturbations have already acted on these flows.

To propel our understanding of how ISD interacts with and is filtered by the heliosphere in the IMAP and post-IMAP era, scientific investigations aimed at making multi-point ISD measurements at various distances towards the upstream ISD flow direction are critical, specifically to characterize the heliosphere's ISD filtration effect (Czechowski and Mann (2003b, Mann 2010), both as a function of grain size and composition. To fully understand how interstellar dust interacts with the heliosphere requires space missions making multi-position measurements across a large range of heliocentric distances. Reaching out to and beyond the heliopause is critical for a full-fledged characterization of the flux and composition of pristine interstellar dust and to understand how the heliosphere filters and interacts with the interstellar dust flow.

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