

JGR Space Physics

RESEARCH ARTICLE

10.1029/2020JA028463

Key Points:

- We combine a heliospheric model a with nanodust dynamics model to trace nanodust grains in inner heliosphere
- Nanodust dynamics and fluxes imprint heliospheric current sheet depending on size
- Model impact rates do not agree with STEREO observations suggesting other sources of time variability

Correspondence to:

A. R. Poppe, poppe@berkeley.edu

Citation:

Poppe, A. R., & Lee, C. O. (2020). The effects of solar wind structure on nanodust dynamics in the inner heliosphere. *Journal of Geophysical Research: Space Physics*, *125*, e2020JA028463. https://doi.org/ 10.1029/2020JA028463

Received 8 JUL 2020 Accepted 25 SEP 2020 Accepted article online 10 OCT 2020

The Effects of Solar Wind Structure on Nanodust Dynamics in the Inner Heliosphere

A. R. Poppe¹ and C. O. Lee¹

¹Space Sciences Laboratory, University of California, Berkeley, CA, USA

Abstract Several interplanetary spacecraft have inferred the presence of nanometer-sized dust grains in the inner heliosphere accelerated to near-solar wind velocities based on observations by radio wave antennas. These "nanodust" grains exhibit unique behavior in interplanetary space as they are strongly affected by both the solar gravitational force and the electromagnetic Lorentz force from the convecting interplanetary magnetic field. Here, we study the dynamics of nanodust grains in the inner heliosphere via a combination of background electromagnetic fields from the coupled Wang-Sheeley-Arge/Enlil heliospheric model and a nanodust grain charging and dynamics model. The model results predict strong time variability in the nanodust velocity and flux distributions at 1 au within a single Carrington rotation (CR) driven by a combination of nanodust grain size, heliospheric current sheet tilt, and varying heliospheric plasma parameters. In contrast, the general character of nanodust dynamics does not drastically change from one CR to the next. Despite including observationally driven heliospheric plasma conditions, the modeled nanodust impact rates do not agree with in situ observations by the STEREO A and B WAVES instruments, especially with regard to CR-to-CR variability. We interpret this data-model disagreement as evidence that additional time variability must be present in the production rate of nanodust grains in the inner heliosphere. We discuss possibilities for this time variability, including non-steady-state collisional cascades, variability in nanodust trapping regions, and the impulsive disruption of inner solar system comets and/or asteroids.

1. Introduction

Dust created in cometary outgassing and asteroidal collisions pervades interplanetary space. Once liberated from their parent bodies, interplanetary dust grains (IDPs) are subjected to various forces, including solar and planetary gravity, solar radiation pressure and drag (i.e., Poynting-Robertson or P-R drag) (e.g., Burns et al., 1979), and electromagnetism (e.g., Horányi, 1996; Lhotka et al., 2016). Various destructive processes also impact IDPs, including grain-grain collisions (e.g., Borkowski & Dwek, 1995; Stark & Kuchner, 2009), solar wind charged-particle sputtering (e.g., Mukai & Schwehm, 1981), and sublimation (e.g., Kobayashi et al., 2009). Generally speaking, grains larger than ~0.5 µm in radius have a net negative radial drift due to P-R drag and will slowly spiral inward to the inner solar system. As grains drift inward, their physical radii tend to shrink, gradually in the case of solar wind sputtering, rapidly at critical distances in the case of erosive or destructive grain-grain collisions. If the radius of a grain falls below ~0.5 µm, the solar radiation force, F_g (characterized by the ratio, $\beta = F_r/F_g$). Under these conditions, IDPs will reverse their radial drift from inward to outward and rapidly escape the solar system. Such outward-moving grains have long been known to exist and are termed " β meteoroids" (e.g., Grün et al., 1985; Wehry & Mann, 1999; Zook & Berg, 1975).

Grains with radii smaller than ~0.1 μ m (100 nm), often termed "nanodust," however, have β values less 1 (see, e.g., Figure 7a of Burns et al., 1979) due to their inefficient coupling with the dominant solar radiation at wavelengths near 1 μ m. Thus, these grains do not feel significant radiation pressure and are instead predominantly controlled by a combination of gravitational and electromagnetic forces. Some of the first detections of nanometer (sometimes also termed "submicron")-sized dust grains came from observations of Jovian "dust streams" by the Ulysses and Galileo cosmic dust detectors (e.g., Baguhl et al., 1993; Grün et al., 1993) and later Saturnian dust streams observed by the Cassini Cosmic Dust Analyzer (Kempf et al., 2005). Observational analysis (e.g., Graps et al., 2000; Grün et al., 1996; Hsu et al., 2010; Hsu, Kempf, et al., 2011;

©2020. American Geophysical Union. All Rights Reserved.



Krüger et al., 2003; Zook et al., 1996) and modeling (e.g., Horányi et al., 1993, 1997; Hsu, Postberg, et al., 2011) of both the Jovian and Saturnian dust streams demonstrated that nanometer-sized dust grains originating from Io (in the case of Jupiter) and Enceladus (in the case of Saturn) have sufficiently large charge-to-mass ratios such that their dynamics are dominated by the electromagnetic fields of the magnetospheres of Jupiter or Saturn as well as the solar wind. Thus, in the outer solar system at least, complex electromagnetic and gravitational dynamics of nanometer-sized dust is a well-documented and well-understood phenomenon.

Among the many reports of interplanetary dust observations, there is now an extensive body of literature describing the implicit detection of planetary, interplanetary, and interstellar dust grains by radio wave antennas, due to spacecraft potential perturbations induced by hypervelocity IDP impacts on spacecraft bodies. Radio wave antenna detections of dust impacts have been observed by Wind (Kellogg et al., 2016; Malaspina & Wilson, 2016; Malaspina et al., 2014; Wood et al., 2015), Cassini (e.g., Kurth et al., 2006; Wang et al., 2006), STEREO A and B (e.g., Malaspina et al., 2015; Meyer-Vernet et al., 2009), MAVEN (Andersson et al., 2015), Voyager 1 and 2 (Gurnett et al., 1997; Wang, 2004), and Parker Solar Probe (e.g., Malaspina et al., 2020; Mozer et al., 2020; Page et al., 2020; Szalay et al., 2020). These detections span the solar system from distances <0.25 au as observed by Parker Solar Probe to >70 au as observed by Voyagers 1 and 2. Among these various radio wave data sets of dust grain impact detections, a subset of observations by the STEREO A and B WAVES (S/WAVES) instruments have been interpreted as evidence of high-velocity (approximately hundreds of km/s), nanometer-sized dust grains impacting the spacecraft and locally perturbing the photoelectron sheath around a single STEREO antenna (e.g., Le Chat et al., 2015; Meyer-Vernet et al., 2009; Pantellini et al., 2012; Zaslavsky et al., 2012), although this interpretation is not without some uncertainty and criticism (e.g., Kellogg, 2017; Kellogg et al., 2018). One of the dominant features of these observations is the high time variability in the impact rate over a wide range of timescales, ranging from minutes to years. By comparison, the flux of larger grains with radius $a \sim 1-100 \,\mu\text{m}$ that comprise the bulk of the sporadic micrometeoroid background is observed to have far less temporal variability (e.g., Horányi et al., 2015; Janches et al., 2006; Malaspina & Wilson, 2016; Malaspina et al., 2014; Poppe et al., 2011).

Motivated by these observations, previous modeling has elucidated various mechanisms underlying the kinematics of nanometer-sized dust grains interacting with heliospheric plasma and fields. Initial simulations showed that under several straightforward assumptions, one could easily demonstrate that nanometer-sized dust grains born in the inner heliosphere (i.e., ~0.1-0.25 au) would be accelerated radially away from the Sun to a significant fraction of the solar wind speed (e.g., Czechowski & Mann, 2010; Meyer-Vernet et al., 2009). Such high dust grain velocities are critical in explaining the observability of nanodust via impact charge perturbations, as the production of impact charge scales roughly linearly with mass but greater than the velocity cubed. Further modeling by Juhász and Horányi (2013) showed that both the nanodust grain mass and the structure of the heliospheric current sheet (HCS) are dominant factors in controlling the observability of nanodust grains at 1 au. Upon interacting with interplanetary magnetic fields (IMFs), nanodust grains will be accelerated radially outward but will also drift latitudinally, with such drifts dependent on the grain mass (more massive grains drift faster), the polarity of the heliospheric electric fields (either focusing, where interplanetary electric fields point toward the HCS, or defocusing, where electric fields point away from the HCS), and the degree of the HCS tilt (e.g., Hoeksema, 1995; Suess et al., 1993). Finally, it has also been shown that interplanetary coronal mass ejections (CMEs) can have dramatic effects on the behavior of nanodust grains, including acceleration of grain velocities up to \sim 1,000 km/s and the introduction of large and temporally variable longitudinal asymmetries in nanodust fluxes (e.g., Czechowski & Kleimann, 2017; O'Brien et al., 2018).

Despite these modeling efforts, comparisons to the S/WAVES observations of nanodust grain fluxes—in particular, the observed time variability—have not always yielded positive agreement (e.g., Juhász & Horányi, 2013). Alternatively, it has been suggested that temporal variability in the observed nanodust grain fluxes is due not to nanodust grain interactions with heliospheric fields alone but is perhaps also related to a high degree of variability in the production rate of nanodust grains themselves. Temporally variable sources of nanodust grains may include the impulsive release of material from Sun-grazing comets (e.g., Ip & Yan, 2012; Jones et al., 2018) or stochastic collisions between large (greater than meter-sized) objects that locally introduce high concentrations of nanodust grains that are then picked-up and accelerated outward (e.g., Lai & Russell, 2018; Lai et al., 2015). While a determination of the relative contributions of these two effects (i.e., heliospheric interactions or variable production rates) remains an open question, more accurate models of the solar wind structure and variability, and the interaction of nanodust grains therewith, are now

available as tools to gain a clearer understanding. In essence, the greater degree to which we understand the role of heliospheric plasmas and fields on the dynamics of nanodust grains, the better we can discern fingerprints of the processes governing nanodust production in the inner heliosphere.

Here, we present modeling results on the dynamics of nanodust grains originating in the inner heliosphere as they interact with solar wind plasma and IMFs derived from a coupled corona-solar wind model. In section 2, we describe both the heliospheric model and the nanodust dynamics model, describing the new elements brought to the study of nanodust as well as important caveats and limitations. In section 3, we present results from both the heliospheric model and the nanodust model, with a focus on how the heliospheric model leads to complex structures in the nanodust dynamics. In section 4, we compare the nanodust dynamics model results to observations by the STEREO A and B spacecraft. Finally, in section 5, we discuss this comparison and conclude.

2. Model Description

In order to investigate and quantify the interaction of nanometer-sized dust grains with heliospheric structures in the inner solar system, we have used a combination of two models: (1) the coupled Wang-Sheeley-Arge (WSA)-Enlil three-dimensional numerical solar corona-solar wind model and (2) a fully time-dependent dust grain charging and dynamics model. In this section, we describe both models including their inputs and outputs, governing physics, underlying assumptions, and caveats.

2.1. Heliospheric Model

WSA-Enlil is a coupled 3-D modeling system that consists of the semiempirical solar corona model (WSA) (Arge & Pizzo, 2000; Arge et al., 2004) and the numerical magnetohydrodynamic (MHD) solar wind model (Enlil) (Odstrcil, 2003). WSA-Enlil is well tested and widely used for space weather forecasting operations at the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) and for scientific research through the National Aeronautics and Space Administration (NASA) Community Coordinated Modeling Center (CCMC) Runs-on-Request service (available publicly at https://ccmc.gsfc. nasa.gov/requests/requests.php). The WSA corona model uses synoptic photospheric maps obtained from ground observatories (e.g., Mount Wilson Observatory) over a Carrington rotation (CR) (one solar rotation as viewed from Earth, \approx 27.27 days) as input to compute coronal fields and solar wind speeds from 1 solar radius (R_s) out to 21.5 R_s (~0.1 au), the Enlil inner boundary. Enlil then uses the WSA output to simulate the solar wind flow by calculating the solar wind velocity, density, and temperature and magnetic field strength and polarity throughout the inner heliosphere. The default, lower-resolution mode of WSA-Enlil used for this study employs a spherical coordinate system centered on the Sun that spans 0.1-1.7 au radially in 256 logarithmically spaced steps, 360° in longitude in 4° steps, and ±58° in latitude in 4° steps. Comparisons of the modeling results with in situ measurements from ACE at L1 showed that WSA-Enlil can accurately simulate the gross features of the solar wind structure, particularly during the declining phase of Solar Cycle 23 (e.g., Jian et al., 2015; Lee et al., 2009; MacNeice, 2009a, 2009b; MacNeice et al., 2018).

2.2. Nanodust Dynamics Model

The nanodust dynamics model tracks the position, velocity, and charge of individual dust grains in three dimensions as they interact with the solar gravitational field, solar photon irradiance, and the solar wind plasma and electromagnetic fields. At its core, the code solves a coupled set of three differential equations:

$$\frac{d\mathbf{r}(t)}{dt} = \mathbf{v}(t) \tag{1}$$

$$m\frac{d\mathbf{v}(t)}{dt} = \mathbf{F}_{g}(\mathbf{r}, \beta) + \mathbf{F}_{L}(\mathbf{r}, \mathbf{v}, q)$$
(2)

$$\frac{dq(t)}{dt} = I_{ph}(q, S) - I_{swe}(q, \mathbf{r}, t) + I_{swi}(q, \mathbf{r}, t) + I_{see}(q, \mathbf{r})$$
(3)

where **r** is the dust grain position vector, **v** is the dust grain velocity vector, *m* is the dust grain mass, \mathbf{F}_{g} is the solar gravitational force corrected for solar radiation pressure via the β parameter, \mathbf{F}_{L} is the electromagnetic Lorentz force, *q* is the dust grain charge, and I_{ph} , I_{swe} , I_{swi} , and I_{see} are the photoelectron emission current, solar wind electron collection current, solar wind ion collection current, and secondary electron emission



current, respectively. Equations 1 and 2 govern the kinematics of the dust grain position and velocity subject to gravitational, solar radiation, and electromagnetic Lorentz forces. The gravitational force includes the reduction due to solar radiation pressure, that is, the β parameter, although $\beta < 10^{-2}$ for grains with radii <30 nm (e.g., Burns et al., 1979). The Lorentz force includes the magnetic and electric fields interpolated to the instantaneous position of each nanodust grain from the three-dimensional grid of Enlil results. For simplicity, we assume the grains to be composed of astrosilicate material, to be spherical in shape with a constant size (i.e., no sputtering or evaporation), and to have a mean material density of 2 kg m⁻³. We also neglect the Poynting-Robertson and solar wind drag terms as these perturbations are negligible for nanometer-sized grains, especially given their extremely short lifetimes in the inner heliosphere.

Equation 3 governs the charge equilibrium of the dust grain and allows for dynamic changes in the dust grain charge due to changes in, for example, the ambient solar wind density, ion and electron temperatures, and ion speed, which together control the solar wind ion and electron currents to the grains. The expressions for each of the currents were taken from Horányi (1996), which have been successfully used for time-dependent charging of dust grains in previous dust dynamics models at the Moon (Piquette & Horányi, 2017; Poppe & Horányi, 2010; Poppe et al., 2012), Jupiter (e.g., Horányi et al., 1993), Saturn (e.g., Horányi et al., 1992, 2008), and in interplanetary space (Poppe, 2016, 2019). Grain charges are forced to be quantized (i.e., \dots , -1e, 0e, $+1e, \ldots$) using a Monte Carlo method. We note that for nanometer-sized grains, field emission may be an important current to consider. As detailed in Draine and Salpeter (1979), field emission imposes limits on the maximum grain potentials, both negative and positive, respectively, that a grain of a given size can sustain before field emitting. For negatively charged grains, the minimum grain potential is, $\phi_{min} = -1 a_{nm}$, where ϕ_{min} is in V and a_{nm} is the grain radius in nm. For positively charged grains, the maximum potential is given by $\phi_{max} = +30 a_{nm}$. For the simulations presented here, we verified a posteriori that grain potentials stayed within these bounds for all grain sizes (see e.g., Figure 9), and thus, we can safely neglect field emission currents. We caution however, that such an assumption may not necessarily be valid under other, more extreme plasma environments and thus should be carefully checked in those cases.

For secondary electron emission, theoretical analyses and laboratory studies have quantified the secondary emission yield, δ , and peak energy, E_M , of IDPs (e.g., Chow et al., 1993; Dzhanoev et al., 2016; Horányi et al., 1995, 1998; Walch et al., 1995). For nanometer-sized grains, however, yields can be enhanced relative to larger grains and the particular shape of the secondary electron yield as a function of energy is not as well described by the standard Sternglass (1954) function. For our model, we used $\delta = 10$ and $E_M = 750 \text{ eV}$ (see e.g., Figure 3b of Chow et al., 1993) as an estimate for all grain sizes, although we did maintain use of the Sternglass (1954) functional form as it is more analytically tractable (and therefore, more computationally efficient) than the form derived for nanometer-sized grains (Dzhanoev et al., 2016). We note that use of the Sternglass (1954) functional form for $\delta(E)$ as opposed to the form derived in, for example, Dzhanoev et al. (2016) could lead to some discrepancies in the innermost solar system; however, as will be shown later, the equilibrium potential of the nanodust grains is primarily driven by photoemission throughout the domain of study with secondary electron emission occasionally dominating in the innermost solar system under the densest and hottest solar wind electron conditions. A detailed examination of differences in grain charging and dynamics that arise from this assumption is left for future work.

We modeled 10 nanodust grain sizes logarithmically spaced in grain mass, $m = [10^{-23}, 10^{-22.5}, ..., 10^{-19}, 10^{-18.5}]$ kg, and referred to (for convenience) by their approximate radii: 1, 1.5, 2, 3, 5, 7, 10, 15, 20, and 30 nm. Using the electromagnetic fields generated by Enlil for a given CR of interest, we initialized 5×10^5 nanodust grains for each size between the inner boundary of Enlil at 0.1 au and the Earth's orbit at 1.00 au on low eccentricity (e < 0.15) orbits with randomized longitudes of ascending node and arguments of perihelion. Initial grain inclinations, *i* (measured in radians), were initialized according to the distribution,

$$g(i) = \sin(i)\exp(-3i),\tag{4}$$

as determined observationally by Leinert et al. (1976). We did not include any additional velocities imparted to the nanodust grains from the collisional process itself, and thus, newly born nanodust grains are assumed to inherit the velocity of their parent meteoroid as their initial velocity. Grain trajectories were advanced using a Merson integrator (Merson, 1975) with a prescribed error limit of 10^{-6} and instantaneous field values from WSA-Enlil (including the magnetic field vector, electric field vector, plasma density, velocity, and temperature) were calculated at the particle position using trilinear interpolation. To correctly account for





Figure 1. The (a) relative density and (b) relative collision frequency adopted for the parent meteoroid distribution in the inner solar system. The relative density is from the "fan-model" of Leinert et al. (1976) and Leinert et al. (1981) and is assumed to be azimuthally symmetric.

the solar rotation, the WSA-Enlil fields were rotated at each integration time step corresponding to the sidereal CR period of 25.38 days. The state vector of each grain was printed out at a regular intervals and grains were terminated if they (i) reached the inner radial Enlil boundary at 0.1 au, (ii) reached the upper or lower latitudinal Enlil boundaries at \pm 58°, (iii) reached a radial distance of 1 au, or (iv) had total integration times that exceeded 10 CR periods (see section 2.3 regarding this last point).

For this study, we assumed that nanodust grains are continuously produced through grain-grain collisions as part of the zodiacal dust cloud collisional cascade (e.g., Grün et al., 1985). Thus, in order to calculate equilibrium nanodust grain densities, fluxes, and velocity distributions, the ensemble of 5×10^5 grain trajectories modeled for each size must be weighted by an appropriate spatial distribution for grain-grain collisions in the inner solar system. Using photometry measurements of the zodiacal light from both rockets (Leinert et al., 1976) and the Helios 1 and 2 spacecraft (Leinert et al., 1981), we adopted the "fan-model" function for the spatial density distribution of meteoroids in the inner solar system, n(r), as

$$n(r) = r^{-1.3} \exp(-2.6|\sin\beta_{\odot}|), \tag{5}$$

where *r* is the heliocentric distance and β_{\odot} is the ecliptic latitude. This distribution is shown in Figure 1a in normalized units relative to the density

at a position of [r, z] = [0.1, 0.0] au. For comparison, with this model the density at the inner Enlil boundary of 0.1 au is ~50 times the density at 1 au. Using this density distribution, we then estimated the spatial distribution of the collisional production of nanodust grains. The outcome of a grain-grain collision (i.e., cratering, fragmentation, and/or vaporization) is a complex function of material strengths and relative impact sizes and velocities (e.g., Borkowski & Dwek, 1995) and the relative impact velocities are in turn a complex function of the parent meteoroid orbital element distributions (e.g., Greenberg, 1982; Kessler, 1981; Öpik, 1951; Wetherill, 1967). Without resorting to a full analytical or numerical description of this process (e.g., Gáspár et al., 2012; Grün et al., 1985), we make the assumptions that (i) the collisional probability scales as the density squared times the relative grain-grain impact velocity and (ii) the relative impact velocities between parent meteoroids scale in the same fashion as the Keplerian orbital velocities, namely, $v(r) \propto r^{-0.5}$ (see also Czechowski & Mann, 2012). Thus, the collisional production rate, $\Gamma(r)$, for nanodust grains is given by

$$\Gamma(r) = n^2(r) \cdot r^{-0.5} = r^{-3.1} \exp^2(-2.6|\sin\beta_{\odot}|), \tag{6}$$

and is depicted in Figure 1b, normalized relative to the collisional frequency at [r, z] = [0.1, 0.0] au. As discussed in previous modeling work (e.g., Czechowski & Mann, 2010; Juhász & Horányi, 2013), much of the collisional production of nanodust grains is concentrated in the inner heliosphere at distances less than ~0.25 au. Each simulated grain trajectory is then assigned a weight according to the collisional production rate, $\Gamma(r)$, at the starting position of the grain.

Finally, to account for both solar rotation as a function of time and the assumed ongoing production of nanodust grains, we rotate the position and velocity of the nanodust grains at each individual time, *t*, through an angle, $\phi(t) = -2\pi(t/t_{CR})$, where the simulation for each grain always starts at t = 0. Here, we use the synodic CR period at 1 au, $t_{CR} = 27.27$ days, so that we arrive in a frame of reference where Earth is always located along the *x* axis at 1 au. In formal terms, this coordinate frame is the Heliocentric Earth Equatorial (HEEQ) frame (e.g., Fränz & Harper, 2002). As will be shown below, this rotation then naturally gives rise to structures in the nanodust density and fluxes similar to the Archimedean spiral of the solar wind and IMF (e.g., Parker, 1958). We do note that because the HEEQ frame is vertically oriented along the solar rotation axis as opposed to the ecliptic north axis, the apparent latitude of an observer in the ecliptic plane at 1 au varies by $\pm 7.25^{\circ}$ due to the solar obliquity.

2.3. Model Assumptions and Limitations

We briefly discuss here several important assumptions and limitations for this study that should be kept in mind. First, the reliable production of modeled background solar wind by WSA-Enlil is dependent on the



accuracy of the input synoptic map of the photospheric magnetic field (for details, see Arge & Pizzo, 2000; Arge et al., 2004; Ulrich et al., 2002). During quiet solar conditions, the coronal fields are relatively static in comparison to active solar periods when there are more frequent eruptions, such as solar flares or CMEs, both of which yield a more complex and time-variable heliospheric environment. Additional information on the general assumptions utilized by the WSA and Enlil models may be found in previous literature (e.g., Arge et al., 2004; Lee et al., 2009, 2011; Odstrcil, 2003). WSA-Enlil does not account for any self-consistent impacts that charged nanodust grains may have on the evolution of the solar wind. Injection of newly born dust may locally perturb the solar wind parameters if the nanodust mass distribution is dense enough due to, e.g., cometary sublimation or massive collisions (e.g., Jia et al., 2012; Lai & Russell, 2018; Rasca, Horányi, et al., 2014; Rasca, Oran, et al., 2014). We have assumed the nanodust production to be constant in time, azimuthally symmetric, and with proscribed-albeit observationally constrained-radial and orbital element distributions (Leinert et al., 1976, 1981). These spatial density distributions and our estimation of the spatial distribution of collisional production of nanodust grains may not be fully accurate, in particular in the nanometer particle size regime. Furthermore, previous work has suggested that nanodust grain production rates may be temporally variable due to changes in the theoretical boundary of the nanodust trapping region inside ≈0.2 au (Czechowski & Mann, 2010) or in the case of rapid sublimation of sungrazing comets (Ip & Yan, 2012; Jones et al., 2018); however, we do not consider these potential generation mechanisms in this study. We also do not consider the presence of any solar flares or CMEs, which are known to significantly perturb the interplanetary environment and nanodust grain charging and dynamics (e.g., Czechowski & Kleimann, 2017; O'Brien et al., 2018; Sternovsky et al., 2008). Finally, when modeling nanodust grain dynamics, some grains have lifetimes in the simulation domain that are longer than a CR period. Using the WSA-Enlil field values for a given CR at times past a CR period is not fully accurate, as the underlying solar photospheric maps will have evolved. A more accurate approach would be to use the WSA-Enlil results for the next CR at each successive sidereal period or to successively update the WSA-Enlil results with updated solar photospheric observations at roughly daily cadence; however, both of these approaches are computationally intensive and beyond the current scope of our research. With these caveats and limitations in mind, we proceed to present the model results.

3. Model Results

3.1. WSA-Enlil

For an initial study, we identified a relatively quiet solar period that overlapped with the STEREO mission, CR 2052 (8 January 2007 to 4 February 2007) and simulated the solar wind conditions using the WSA-Enlil model at the NASA CCMC. Figure 2a shows the source surface magnetic field strength at 2.5 solar radii as obtained from the Wilcox Solar Observatory (WSO). During CR 2052, the solar dipole has a tilt of approximately 30°, and the HCS has a corresponding sinusoidal structure in latitude. The maximum latitudinal extent of the HCS is approximately -30° in the southern hemisphere and $+15^{\circ}$ in the northern hemisphere. Figures 2b-2e show the Enlil results, including the magnetic field magnitude, solar wind density scaled by r^2 , solar wind temperature, and solar wind velocity in the HEEQ equatorial plane. In this reference frame, Earth is located at a position of [x, y] = [1.0, 0.0]. Overall, the solar wind structure during CR 2052 is dominated by four sectors alternating azimuthally in slow and fast solar wind, Figure 2e. The slow wind sectors have median speeds of ~300 km/s, and the two fast wind sectors have peak speeds of approximately 525 and 650 km/s, respectively. The solar wind density, Figure 2c, possesses similar four-sector structure, with higher densities associated with slow solar wind sectors and lower densities associated with fast solar wind sectors. Furthermore, several stream interaction regions are seen at boundaries between fast and slow wind sectors (e.g., Gosling & Pizzo, 1999; Hundhausen, 1973). The plasma temperature, Figure 2d, possesses similar four sector structure, with the fast streams generally hotter than slow streams. Furthermore, the temperature possesses a negative radial gradient such that at 1 au the temperature is $\sim 10 \text{ eV}$ while at the inner boundary of Enlil at 0.1 au the temperature is $\sim 100 \text{ eV}$. Such radial variations in solar wind temperature are also observed in situ (e.g., Maksimovic et al., 2000; Marsch et al., 1989; Pilipp et al., 1990; Sittler & Scudder, 1980).

The WSA-Enlil results for CR 2052 shown in Figure 2 can be compared to in situ observations in order to assess to some degree the overall quality of the model results. In Figure 3, we compare the solar wind density, magnetic field strength, and solar wind velocity between the WSA-Enlil results (red) and the OMNI plasma and field data set (black) (King & Papitashvili, 2005) at 1 au. Overall, the WSA-Enlil results capture





Figure 2. (a) The source surface magnetic field strength for CR 2052 from the Wilcox Solar Observatory (WSO). (b–e) The WSA-Enlil results for the scaled density and velocity in the HEEQ equatorial plane for Carrington Rotation 2052. The Earth's position is denoted by the black dot at [+1.0, 0.0], and the Earth's orbit is denoted by the dashed circle.

the gross features of the solar wind parameters at 1 au reasonably well, including the two fast stream sectors centered on approximately 19 and 31 January, respectively, and a pair of magnetic field compressions near 15 and 29 January, respectively. The solar wind density is very well reproduced for dates after approximately 15 January. Disagreements between WSA-Enlil and OMNI are seen, however, in the lack of capture of a moderate velocity stream (~500 km/s peak) and corresponding deep density depression ($n \sim 0.5$ cm⁻³) near 12 January. Also, the first magnetic field compression seen in the WSA-Enlil results appears on 14 January while the compression appears in the OMNI data set slightly later on 15 January. These disagreements may in part be due to the specification of the input photospheric magnetic field as observed by Mt. Wilson Observatory (vs. by another observatory, such as the WSO). For the purpose of our study, we consider this agreement satisfactory, in particular, the reproduction of many of the *gross* features of the solar wind, while





Figure 3. A comparison of the solar wind density, magnetic field magnitude, and solar wind velocity between WSA-Enlil (red) and Wind (black) for Carrington Rotation 2052.

noting that differences between the model and observations exist and that such differences may impact the results of the nanodust dynamics model.

3.2. Nanodust Dynamics

3.2.1. CR 2052, 10 nm Grain Size

In Figure 4, we show a synthesis of results from the nanodust dynamics model for 10 nm grains during CR 2052, including (a) the nanodust flux within $\pm 7.25^{\circ}$ ecliptic latitude of the HEEQ equatorial plane (i.e., those grains that would be visible at Earth) scaled by r^2 , (b) the azimuthally averaged flux in cylindrical HEEQ coordinates, (c) the angular (i.e., longitudinal and latitudinal) flux distribution at 1 au, and (d) the impact velocity distribution at 1 au assuming an observer in a circular Keplerian orbit with orbital speed \approx 30 km/s. The flux distribution in the HEEQ equatorial plane, Figure 4a, varies over approximately 2 orders of magnitude and possesses a significant degree of structure as a function of longitude, strikingly reminiscent of Parker spiral-type structures in the solar wind. One underlying reason that this structure is present in the nanodust grain flux is due to a "projection effect" since Figure 4a only includes grains within $\pm 7.25^{\circ}$ of the HEEQ equatorial plane. In Figure 4c, the angular distribution of nanodust grain flux at 1 au is warped above and below the HEEQ equatorial plane as the peak in the azimuthal nanodust grain flux follows the HCS structure closely (i.e., due to nanodust "surfing" of the HCS during focusing IMF conditions (e.g., Czechowski & Mann, 2010; Juhász & Horányi, 2013). Taking only those grains whose trajectories fall within the $\pm 7.25^{\circ}$ latitudinal region (denoted in Figure 4c with the innermost pair of dotted black-and-white lines), one arrives at the variability present in Figure 4a. As shown in Figure 4b, the meridional distribution of nanodust grain fluxes is primarily concentrated within $\approx \pm 30^{\circ}$ latitude. Fluxes drop by several orders of magnitude at latitudes greater than $\approx \pm 40^{\circ}$. Near the HEEQ equatorial plane, fluxes drop approximately 2 orders of magnitude from the inner boundary at 0.1 au out to 1 au. Finally, Figure 4d shows the impact velocity distribution and the median impact velocity (dashed black-and-white line) as a function of HEEQ longitude. Impact velocities extend from minima near ≈ 0 km/s to a maximum of ≈ 500 km/s. The median impact velocity (black-white dashed line) inhabits a narrower range between approximately 200 and 350 km/s with variations partially associated with changes in the nanodust grain flux.

3.2.2. CR 2052, All Grain Sizes

Figure 5 shows the flux of nanodust grains for all 10 sizes taken within $\pm 7.25^{\circ}$ of the HEEQ equatorial plane run during CR 2052. The flux values are individually normalized to their own respective maxima, as we have not yet attempted to calculate absolute nanodust grain production rates by size. Across all 10 sizes, nanodust fluxes share the general Parker spiral-like shape due to the combination of solar rotation, which controls the electromagnetic field structures responsible for accelerating nanodust grains, and the outward radial motion of the nanodust grains, which depends on grain size (Czechowski & Mann, 2010). As sizes increase,



Figure 4. Nanodust model results for 10 nm grains during CR 2052, including (a) the flux in the HEEQ equatorial plane, (b) the azimuthally averaged flux, (c) the flux at 1 au as a function of HEEQ longitude and latitude, and (d) the dust grain velocity distribution as a function of HEEQ longitude. In panel (b), the horizontal dashed line denotes the HEEQ equator and the dotted lines denote the boundaries of the WSA-Enlil model. In panel (c), the dotted lines mark the upper and lower azimuthal boundaries of the WSA-Enlil model and the black-and-white dashed lines mark the $\pm 7.25^{\circ}$ latitudinal extent of the Earth's position in the HEEQ frame. In panel (d), the dashed line denotes the median impact velocity as a function of HEEQ longitude.





Figure 5. (a-j) The nanodust grain fluxes in the HEEQ equatorial plane for each of the 10 nanodust sizes for CR 2052.

the apparent degree of structure in the equatorial nanodust grain fluxes generally increases. For example, the flux distributions of 1, 1.5, 2, 3, and 5 nm dust grains shown in Figures 5a–5e only somewhat imprint the underlying solar wind density structure for CR 2052 (as seen in Figure 2a), while the 7, 10, 15, and 20 nm nanodust flux distributions, Figures 2f-2i, show greater degrees of azimuthal and radial structure. As noted for the 10 nm example in Figure 4, the "ridges" of higher nanodust flux seen in, for example, the 7, 10, 15, and 20 nm sizes are located approximately where the HCS crosses the $\pm 7.25^{\circ}$ HEEQ latitudinal window. As will be discussed below for Figure 6, nanodust grain "surfing" of the HCS is maximized for this size range, contributing to the appearance of strong azimuthal variability. We further note that as the nanodust grain sizes increase, the azimuthal wrapping of the nanodust grain flux ridges increase. In the 1 nm case, Figure 5a, typical flux "ridges" rotate approximately 30° in longitude from 0.1-1 au, while for 30 nm, Figure 5j, some ridges can be followed through nearly 180° of rotation by the time they reach 1 au. This variation is an indication that the radial component of the typical nanodust grain velocity decreases as a function of size, similar to that seen in previous simulations (e.g., Czechowski & Mann, 2010) (see further discussion of the nanodust velocity distributions below). Note also that at 1 au, ridges in the nanodust flux for the largest size (30 nm, Figure 5j) have largely blended together resulting in a more azimuthally symmetric flux than that seen for smaller grains.

Much of the structure in Figure 5 can be understood by examining the longitudinal and latitudinal distributions of nanodust fluxes at 1 au, shown in Figure 6 for all 10 nanodust grain sizes. These distributions highlight the varying degrees to which nanodust grain fluxes are concentrated along the HCS (shown in each panel of Figure 6 as the dashed black-and-white curve) as a function of grain size. From the smallest sizes of 1 nm up to approximately 5 nm, Figures 6a-6e, the azimuthal flux distribution does not correlate strongly with the position of the HCS, although smaller variations are seen, presumably in response to differing plasma and field environments between, for example, fast and slow wind sectors. For sizes between approximately 7 and 15 nm, Figures 6f-6h, the distributions show an increasing imprint of the four-sector HCS structure, with peak nanodust grain fluxes closely aligned with the HCS position. For the largest grain sizes (i.e., 20 and 30 nm), this trend of closer alignment with the HCS diminishes and the distributions become smoother in both longitude and latitude. Peak nanodust grain fluxes also begin to lag in longitude behind the HCS, as seen near -90° to -45° longitude between the nanodust flux and the HCS. In particular, the latitudinal position of the peak 30 nm grain flux is significantly out of phase with the HCS current latitude is several longitudinal regions. Again, grain sizes that more closely follow the HCS position yield greater structure and variability at 1 au as seen in Figure 5, as the maximum latitudinal extent of the HCS for CR 2052 extends to $+15^{\circ}$ and -30° above and below the HEEQ equatorial plane, respectively, yet fluxes at latitudes $> \pm 7.25^{\circ}$ are not visible at Earth at 1 au.

Figure 7 shows the impact velocity distributions of the nanodust grains onto an object on a Keplerian orbit at 1 au within $\pm 7.25^{\circ}$ ecliptic latitude as a function of HEEQ longitude. Overall, the median impact velocities of nanodust grains at 1 au decrease with grain size as expected, as previous modeling has shown the





Figure 6. (a–j) The azimuthal distribution nanodust grain fluxes in the HEEQ equatorial plane for each of the 10 nanodust sizes for CR 2052.

size dependence of electromagnetic acceleration of nanodust grains in the solar wind (e.g., Czechowski & Mann, 2010). Superimposed on this general trend, however, are more detailed patterns in the velocity distributions for different grain sizes. The velocity distributions for 1, 1.5, 2, 3, and 5 nm grains, Figures 7a–7e, peak in occurrence at impact velocities between approximately 200 and 500 km/s, with the highest impact velocities up to ~800 km/s. There is a high degree of longitudinal variation in the impact velocities, reflecting the underlying four-sector solar wind velocity structure seen in Figure 2e. Intermediate-sized grains, including 7, 10, and 15 nm, have overall slower impact velocities than their smaller counterparts, with maximum velocities between 300 and 600 km/s. These sizes also show a high degree of longitudinal variability, with distinct "bursts" of nanodust grains centered at ~250 km/s. These "bursts" correspond to the longitudinal, Archimedean-spiral structures seen in Figures 5e–5h. Finally, the largest sizes, 20 and 30 nm, have the slowest velocities with maxima of 300 and 200 km/s, respectively, and smoother variation as a function of heliocentric longitude. There is a small degree of dispersive structures visible in these sizes, corresponding to dispersion in the radial velocity of these grains, which controls both their arrival time and heliographic longitude at 1 au.





Figure 7. (a-j) The nanodust impact velocity distributions as a function of HEEQ longitude at 1 au for all 10 sizes for CR 2052.

A comparison of the WSA-Enlil solar wind velocities at 1 au and the median velocities for each nanodust grain size as a function of HEEQ longitude at 1 au is shown in Figure 8. This comparison helps to reveal the degree to which nanodust grain velocities are driven by the local solar wind structures. For grain sizes between 1 and 7 nm, median nanodust velocities correlate well with the local solar wind velocity as shown by the coincident peaks near 45° and 235° longitude, for example. The linear correlation coefficient between the solar wind velocities and the median nanodust velocities for these sizes is between +0.65 to +0.75. The 10 nm grains partially correlate with the solar wind velocity, with a correlation coefficient of +0.41. Visual inspection of the 10 nm median velocity shows peaks coincident with the WSA-Enlil solar wind velocity; however, a higher degree of structure and variability in the median velocity is seen relative to smaller-sized grains. The largest-sized grains, including 15, 20, and 30 nm, have velocities that are essentially uncorrelated, with coefficients between 0.0 and -0.17, although, local increases in nanodust grain median velocities can be seen "lagging" behind local peaks in the solar wind velocity. Specifically, the 15 and 20 nm median velocities have local peaks between 60° and 100° as well as between 270° to 310°. Finally, the 30 nm grains have nearly constant median velocities across all longitudes with little correlation to the background solar wind velocity. Thus, we find that the degree of correlation between nanodust velocities and the solar wind velocities at 1 au is strongly dependent on the nanodust grain size.

As discussed in section 2.2, a unique capability in our nanodust model is the ability for the nanodust grains to dynamically charge as a function of time according to local plasma and solar irradiance conditions. During each simulation, the instantaneous grain charge was recorded at regular time intervals for each grain and accumulated into arrays as a function of heliocentric distance. The discrete grain charges were converted to grain potential via the formula, $\phi = Q_e/700a_\mu$, where ϕ is the grain potential, Q_e is the grain charge in



Figure 8. A comparison of the WSA-Enlil solar wind speed at 1 au (black) and the median nanodust grain impact velocities at 1 au (colors) as a function heliocentric longitude.

units of fundamental charge, and a_{μ} is the grain radius in units of microns (Horányi, 1996). Figure 9 shows the grain potential distribution as a function of heliocentric radial distance for each of the 10 simulated grain sizes, respectively. Note that because the grain capacitance ($C = 700a_{\mu}$) is proportional to the grain radius, smaller grains obtain larger surface potentials with relatively smaller number of charges while larger grains obtain similar potentials only with a relatively large number of discrete charges. This explains the varying "resolution" in grain potential as a function of size seen in Figure 9; for example, a single charge on a 1 nm grain yields a surface potential of ~1.4 V, while a single charge on a 30 nm grain is equivalent to only ~0.05 V. As newly initialized grains are integrated forward in time, they gain charge (either positive or negative) according to locally driven currents, although we do note that grain charging timescales are inversely proportional to grain size (Horányi, 1996).





Figure 9. (a-j) The nanodust grain potential distributions as a function of radial distance for all 10 sizes for CR 2052.

With these points in mind, we note that a majority of all grains charge to potentials on the order of +10 V, somewhat higher than the $\sim+5$ V typically expected in the solar wind (e.g., Horányi, 1996). Equilibrium potentials slightly decrease for all grain sizes from the inner model boundary of 0.1 au to the outer boundary at 1.0 au. For smaller grain sizes, an additional population of grains with lower potentials exists, extending down to 0 V for the smallest 1 nm grains. This population represents newly born grains at varying heliocentric distances that are slowly achieving current equilibrium as they are accelerated outward. Given that charging timescales are inversely proportional to grain size, the presence of these lower potential grains is greater in heliocentric distance for smaller grains than for larger grains. We also note the presence of multiple maxima in the grain potential distributions at given heliocentric radii, which is due to the azimuthal variability in the heliospheric plasma parameters, for example, as seen in Figure 2. While the photoemission current density remains constant azimuthally, the varying plasma parameters as a function of heliocentric longitude yield different equilibrium charge states as grains evolve radially outward.

Overall, the current balance shown in these distributions is driven by varying contributions from three of the main nanodust charging currents: photoemission, electron collection, and secondary electron emission (induced by primary electrons). Ion collection, representing a positive current to the grains, is typically much smaller. For our simulations here, we have set the photoemission current to be constant in time, although we note that this current does change over a solar cycle and during solar flares (Sternovsky et al., 2008). Spatially, photoemission scales simply as r^{-2} . In contrast, the electron collection and secondary electron emission currents are more complex in both space and time due to the varying heliospheric plasma parameters



Figure 10. The average (solid lines) and maximum (dashed lines) nanodust grain charging current densities as a function of heliocentric distance for CR 2052.

within the WSA-Enlil model results. To illustrate this, Figure 10 shows the average and maximum values for all four charging current densities in the model as a function of heliocentric distance, using the Enlil heliospheric parameters from CR 2052 (e.g., Figure 2) as input. Analysis of the theoretical charging currents shown in Figure 10 shows that beyond ~0.50 au, photoemission (red curve) is the dominant charging current regardless of plasma conditions, as the mean solar wind electron collection, ion collection, and secondary emission currents (solid black, green, and blue curves, respectively) are lower than photoemission outside 0.50 au. Within ~0.50 au, the maximum value of secondary electron emission current density (dashed green curve) is greater than photoemission, representing the densest and hottest solar wind electron distributions from the Enlil model results (e.g., Figures 2c and 2d). Within ~0.15 au, the mean secondary electron emission current density (solid green curve) and the maximum electron collection current density (dashed black curve) overtake photoemission, representing a region in the inner heliosphere where dust grain charging is predominantly



controlled by the solar wind electron flux as opposed to solar ultraviolet (UV) photon flux. One may hypothesize that grains at distances <0.10 au (i.e., the inner boundary of the Enlil simulation used here) are even further controlled by plasma fluxes, which may impact studies of nanodust grain "trapping" close to the Sun (e.g., Czechowski & Mann, 2010); however, such an investigation is left for future work.

4. Comparison to STEREO/WAVES Observations

With the heliospherically driven nanodust dynamics model in place as described above, we can now compare these model predictions to spacecraft observations in an attempt to further understand the generation of nanodust grains in the inner heliosphere. In particular, we compare the nanodust impact rates observed by the STEREO A and B WAVES instruments (Bale et al., 2008; Bougeret et al., 2008; Zaslavsky et al., 2012) to modeled rates calculated using the approach detailed above. Before describing the data-model comparison in detail, we caution that while previous analyses have presented strong evidence that the S/WAVES instruments on both spacecraft are responsive to high-speed nanodust impacts (e.g., Meyer-Vernet et al., 2009; Pantellini et al., 2012; Zaslavsky et al., 2012), the exact details and individual response functions of the instruments are not entirely understood. In particular, differences in both the median count rate magnitudes and the time variability between STEREO A and B have been attributed to differences in antenna geometry between the two spacecraft, but detailed models of the respective sensitivity of WAVES instruments between the two spacecraft do not exist. Nevertheless, we find the comparison below instructive, if only to highlight continuing model-data differences that point toward areas of future research. Finally, given the computationally intensive nature of our modeling approach, which requires running simulations of both WSA-Enlil and the nanodust dynamics model for each individual CR, we have chosen to focus on a limited timeframe for comparison, in particular, CRs 2052 through 2059 (8 January to 14 August 2007).

The STEREO spacecraft were launched in late 2006 with a mission to study the initiation, development, and evolution of CMEs in the inner heliosphere (Kaiser et al., 2008). The S/WAVES instruments onboard both spacecraft have primary scientific goals that include, among others, tracking CME shocks and flare electrons, observing solar radio sources, and measuring in situ electron density and temperatures within CME magnetic clouds (Bale et al., 2008; Bougeret et al., 2008). In addition to the primary observations of these phenomena, it was noted early on in the mission that both sets of antennas were recording frequent and intense voltage spikes, apparent in both the frequency and time domains (Le Chat et al., 2015; Meyer-Vernet et al., 2009; Zaslavsky et al., 2012). Further analysis revealed two classes of impact signals: one in which the voltage spike appeared in equal magnitudes on all three S/WAVES antennas and a second in which signals were dominant on one of the three antennas with roughly order of magnitude less amplitude on the other two antennas (e.g., Figure 3 of Zaslavsky et al., 2012). The first of these (termed "triple-hits") were attributed to micron-sized interplanetary and interstellar dust grains that impacted the spacecraft body, generating an impact plasma cloud of sufficient magnitude to momentarily alter the spacecraft body potential relative to all three antennas (see also Collette et al., 2015). The second set of events (termed "single-hits") were attributed to fast-moving (approximately hundreds of km/s), nanometer-sized IDPs that impact close enough to one of the three antennas on each spacecraft (the +X antenna on STEREO A and the +Z antenna on STEREO B) to momentarily disturb the quasi-static photoelectron sheath surrounding the antenna length (Pantellini et al., 2012). This disturbance registers as a strong potential spike in the affected antenna with smaller (by approximately an order of magnitude) signals on the other two antennas. For our comparison here, we used impact rates determined previously by Zaslavsky et al. (2012) from the S/WAVES Time Domain Sampler (TDS) data set, although we do note that Zaslavsky et al. (2012) did establish a high degree of correlation between the nanodust impact fluxes determined separately from the TDS and Low Frequency Receiver (LFR) data sets (Meyer-Vernet et al., 2009).

In order to compare the nanodust dynamics model to the S/WAVES impact rates, we performed several additional modeling steps. For each CR between 2052 and 2059, we simulated the solar wind conditions using the WSA-Enlil model at the NASA CCMC. As input into WSA, photospheric maps from WSO were selected for each CR. Identically to that described for CR 2052 above in section 2.2, we ran 500,000 nanodust grain trajectories for each of 10 sizes for each of the eight CRs, thereby building a library of nanodust grain flux and velocity distributions as a function of time. From this library, we then derived modeled hit rates at both the STEREO A and B spacecraft positions in the HEEQ coordinate frame. First, we calculated the impact charge distributions generated from the impact of nanodust grains onto a solid surface (e.g., the STEREO





Figure 11. (a–j) The nanodust impact charge distributions as a function of HEEQ longitude at 1 au for all 10 sizes for CR 2052. The pair of horizontal dashed lines denote the range of impact charges considered detectable in the analysis of the STEREO WAVES TDS data set (Zaslavsky et al., 2012).

spacecraft body) in order to examine the ability of the S/WAVES instruments to observe such impacts. Using the scaling law for the impact charge, *Q* in Coulombs, given by

$$Q \approx 0.7 m^{1.02} v^{3.48},\tag{7}$$

where *m* is the grain mass in kg and *v* is the grain impact velocity in km/s (McBride & McDonnell, 1999), we calculated the distribution of impact charge for each of the 10 modeled grain sizes as a function of HEEQ longitude. Based on the analysis of Zaslavsky et al. (2012), we selected only those nanodust grains that registered impact charges with magnitudes, $8 \times 10^{-14} < Q < 4 \times 10^{-12}$ °C. This range of impact charges corresponds to the approximate range of induced potentials for single hits (3–150 mV) on the S/WAVES antennas. Second, the nanodust grain fluxes must be appropriately weighted as a function of grain size. The size (or mass) distribution of collisionally produced dust grains is typically assumed to obey a power law distribution in mass as $f(m) \propto m^{-(\eta+1)}$, where *m* is grain mass and $\eta = 0.8333$, with $\int mf(m)dm = m_{tot}$, where m_{tot} is the total fragmented mass (e.g., Borkowski & Dwek, 1995; Dohnanyi, 1969; Grün et al., 1985). The relative production rates of the 10 modeled nanodust grain sizes were weighted by f(m) using the value of the grain mass, *m*. Finally, the model distributions of nanodust grain fluxes and velocity distributions were interpolated to the positions of STEREO A and B, respectively, in the HEEQ coordinate frame as a function of time.

In Figure 11, we show the impact charge distribution as a function of heliocentric longitude for each size (before weighting by the mass production law) for CR 2052, as an example. The range of impact charges detectable as single hits by S/WAVES is denoted by the pair of horizontal dashed lines in each panel (Zaslavsky et al., 2012). Given the strong dependence of the impact charge on impact velocity ($Q \propto v^{3.48}$), the distributions shown in Figure 11 have similar forms to the velocity distributions shown in Figure 7, with variations in the magnitude of the impact charges correlating well with changes in the solar wind speed (e.g., see Figure 8). For the smallest grain size of 1 nm, only small fractions of grain impacts register sufficient charge to be detected near -135° and $+30^{\circ}$ heliolongitude with most grains registering impact charges 1 to 2 orders of magnitude less than the minimum detectable value. The 1.5, 2, and 3 nm grain impact charge distributions have increasing fractions that register above the minimum S/WAVES threshold, although we note that these portions are at specific longitudes and thus contribute further to impact rate variability as a function of time (in other words, nanodust fluxes are present at all longitudes, but smaller grains are only detectable at certain longitudes). For larger sizes, the grain mass and therefore the typical impact charge magnitude increase such that for 5 and 7 nm sized grains, nearly all impacts fall squarely within the detectable range, despite the fact that impact velocities trend lower as a function of grain size. The increase in impact charge due to the increase in grain mass tends to outweigh the simultaneous decrease in impact charge due to the decrease in impact velocities. For grains greater than or equal to 10 nm radius, significant fractions of impact charges are in fact higher than the upper S/WAVES voltage threshold and thus, while detectable, will saturate the instrument. Finally, for the largest-sized grains of 30 nm, we note that while the highest

Figure 12. (top panel) The total modeled nanodust flux (in arbitrary units) to STEREO A and B as a function of time (in Carrington rotations). (lower panels) The size distribution of the modeled nanodust flux for STEREO A and B, respectively.

concentration of impact charges are still either within or above the range of detectability, an increasing fraction of the impact charges now falls below the minimum detectable limit again. This is due to the continued decrease in impact velocities as a function of size seen in Figure 7, as 30 nm (and presumably larger) grains are inefficiently accelerated by heliospheric fields compared to smaller grain sizes.

Thus, taking into account the assumed power law size distribution for grain production and the magnitude of impact charge generated by nanodust grains striking a solid surface, we can compute the modeled nanodust flux summed over all sizes to both STEREO A and B for all eight CRs, 2052-2059, up to a total normalization factor. In Figure 12, the top panel displays the total impact rate for each probe summed over all sizes, while the lower two panels display the contributions to the impact rates as a function of size for both probes, respectively. Note that the absolute values of the fluxes displayed are arbitrary. Due to their close proximity early in this time period, the total fluxes predicted at both STEREO A and B are essentially identical during CRs 2052-2055. Starting in CR 2055, the flux to STEREO B (red) begins to increasingly precede the flux to STEREO A (blue), although the structure of the predicted flux remains very similar. Since STEREO B drifts backward in longitude with respect to the Earth while STEREO A drifts ahead, solar wind and nanodust grain structures rotating in the positive sense pass STEREO B first, then Earth, and then STEREO A. By the end of the modeled period in CR 2059, the fluxes modeled at STEREO B precede those at STEREO A by approximately 2 days. A dominant feature of the modeled nanodust grain fluxes at both probes is the high degree of temporal variability, as seen in both the total flux (top panel) and the flux broken down by size contribution (lower panels). The total nanodust flux in this time period varies by more than a factor of 50, with several large and abrupt increases (e.g., at times of 2052.75, 2054.75, and 2057.75). In the differential flux as a function of size, shown in the lower two panels of Figure 12 for STEREO A and B, respectively, the model predicts that the largest contribution to the overall fluxes comes from nanodust grains of sizes 2 and 3 nm, which together account for ~65% of the flux. Smaller 1 and 1.5 nm grains, while produced in greater numbers overall due to the assumed power law size distribution in mass production, register fewer hits above the minimum detectable impact charge (see Figure 11), accounting for only \sim 15% of the total detectable flux. Sizes of 5 nm and greater contribute increasingly lower fractions to the overall flux, driven primarily by their decreasing number production. In total, grains between 5 and 30 nm produce $\sim 20\%$ of the total detectable flux. Finally, one can also see in the differential flux distributions that increases in the nanodust flux do not happen simultaneously in time across all sizes. Referring back to the two-dimensional, equatorial projections of the nanodust grain fluxes for different sizes shown in Figure 5, one sees that varying degrees of rotation in the structures seen in the nanodust flux as a function of size underlie this behavior.

Figure 13. A comparison of nanodust modeling and STEREO A and B WAVES TDS hit rates for Carrington rotations 2052–2059.

Finally, Figure 13 shows a comparison of the STEREO A and B hit rates calculated from the WAVES TDS observations (Zaslavsky et al., 2012) with the nanodust grain model predictions from Figure 12, top panel. For STEREO A and B separately, we calculated the mean observed daily impact rate and scaled the model curves such that the mean model impact rate matched that of the data. We note that the mean rates between the two STEREO spacecraft differ by a factor of four during this time period (≈ 16 hits day⁻¹ for A and \approx 4 hits day⁻¹ for B). Furthermore, we emphasize again that we do attempt to constrain the overall magnitude of the hit rates to STEREO A or B as there is considerable uncertainty regarding the absolute value of the observed rates (e.g., see discussion in Zaslavsky et al., 2012) but rather focus on the time variability of the impact rates at each spacecraft. As is easily seen for both spacecraft, the observed and modeled hit rates do not agree, especially with regards to the time variability. The model does not capture many of the abrupt and large-scale transitions in the relative magnitude of the nanodust flux, where observed count rates jump sharply, both up and down, by over a factor of 10. In particular for STEREO A, the model does not capture the multi-CR dropout in flux from CR 2053.5 to CR 2059. During this period, we verified that the spacecraft attitude pointing on both STEREO A and B cannot be responsible for the abrupt changes in the nanodust flux (i.e., by potentially changing the apparent cross section of the STEREO spacecraft and/or the response function of the S/WAVES antenna to impacting nanodust grains). Quantitatively speaking, the correlation coefficients between the model and data for STEREO A and B are -0.3 and +0.04, respectively. In the following section, we discuss several potential hypotheses for the disagreement between the nanodust model results and the S/WAVES observations.

5. Discussion and Conclusion

As shown in Figure 12, our modeling results for multi-CR lengths of time show that while nanodust dynamics can be highly variable within a given CR, the qualitative behavior of nanodust grain fluxes at 1 au does

not drastically change from one CR to the next. During CRs 2052–2059, any given CR tends to have approximately an order-of-magnitude variation in nanodust grain flux due to the rotational passage of individual nanodust flux "streams" (e.g., similar to the passage of stream interaction regions); however, the mean nanodust flux over a CR remains relatively constant (not shown). Underlying this behavior—at least over this relatively short time period—are the relatively constant conditions of the solar photospheric fields, the solar corona, and ultimately, the solar wind. As discussed in previous modeling exercises (e.g., Czechowski & Mann, 2010; Juhász & Horányi, 2013), the detectability of nanodust grains at 1 au is strongly driven by the solar magnetic dipole tilt and polarity, which again, do not significantly change over the eight CR-long time period studied here.

Nevertheless, the model-data comparison exercise above shows that our understanding of nanodust dynamics in the inner heliosphere and their detection by the STEREO A and B spacecraft remains incomplete. Despite including observationally driven heliospheric plasma and field structures and making a series of reasonably well-founded assumptions, our model appears to be missing at least one, if not several, key elements critical to understanding nanodust dynamics. Broadly speaking, the underlying reasons for this discrepancy can be organized into several categories, specifically, a lack of sufficient knowledge of (i) the temporal and spatial dependence of nanodust grain production, (ii) the full structure of heliospheric plasmas and fields and the interaction of nanodust grains therewith, and (iii) the detailed—and spacecraft dependent—response function of the S/WAVES antennas to impacting nanodust grains. Any or all of these areas could be contributing to the lack of model-data agreement. Below, we discuss in further detail each of these categories and identify areas in which future research could prove most fruitful.

In our study here, we have assumed that nanodust grains are continuously produced throughout the inner heliosphere via a collisional cascade at a constant rate in time with a smoothly varying spatial distribution (e.g., see Figure 1). While the basic assumption of a steady-state collisional cascade is highly plausible based on previous studies (e.g., Grün et al., 1985; Stark & Kuchner, 2009), it could be either that the collisional cascade is not fully steady state or that the production of nanodust grains from the collisional cascade is not in fact the dominant production method. In the case of the former (i.e., a non-steady-state collisional cascade), previous theoretical work has shown that relaxing certain assumptions and/or including additional physical processes into models of collisional cascades can lead to a variety of effects, including the presence of "waves" in the particle size distributions (e.g., Löhne et al., 2008; O'Brien & Greenberg, 2005; Pan & Schlichting, 2012). If such theoretical studies hold when extrapolated to the nanometer-sized regime (e.g., Löhne et al., 2008) and if such waves are even weakly time dependent, then one could hypothesize that variations in the observed nanodust grain flux are signatures of "wave breaking" in the mass distribution, whereby large amounts of mass are rapidly deposited into the nanometer-sized regime. These wave-breaking events could then be detected at 1 au as sharp increases in outward-accelerated nanodust grain flux.

Alternatively, even under the assumption of a steady-state collisional cascade, it has been suggested by Czechowski and Mann (2012) that changes in the magnetic field structure in the inner heliosphere within ~0.2 au could stochastically release nanodust grains from regions with previously trapped nanodust orbits (Czechowski & Mann, 2010). In particular, this detrapping effect could plausibly be consistent with the requirement of producing a far greater number of nanodust grains than the background, steady-state collisional cascade. As shown in Figure 1b and in Equation 6, the collisional production rate scales steeply as the heliocentric distance, r, implying that a significant fraction of all nanodust grains could be produced solely within the Czechowski and Mann (2010) trapping zone. Thus, even small perturbations of the boundary or effectiveness of the trapping zone could then, in theory, release a far greater number of nanodust grains into untrapped orbits than are generated via collisions just outside the trapping zone. Simulations that model the time-dependent behavior of the solar wind and solar corona within 0.15 au and the subsequent effects on trapped nanodust orbits could address this possibility.

In the case of the latter hypothesis (i.e., that the steady-state collisional cascade is not dominant), one must turn to potential sources for nanodust grains that have strong time dependence. An idea put forward by (Ip & Yan, 2012) is that Sun-grazing comets may provide a significant amount of mass in the nanometer-sized regime as they rapidly shed mass and even disintegrate upon passage through the inner heliosphere (e.g., Jones et al., 2018). In addition to Sun-grazing comets, low-perihelion (q < 0.2 au) asteroids are also thought undergo supercatastrophic breakup due to thermal effects (Granvik et al., 2016). In particular, cometary disruption could be invoked to explain the longer-term behavior of nanodust grain fluxes on

STEREO A, which tend to appear in aperiodic bursts that range in length from ~25 to 100 days (e.g., Figure 8, Zaslavsky et al., 2012). While perhaps coincidental, near-Sun comets with eccentricities of 0.9 < e < 0.99 and perihelia of 0.05 < q < 0.30 au spend between approximately 60 to 150 days within 1 au, timeframes that are commensurate with the bursts seen on STEREO A. It is important to note, however, that in addition to being localized in time, near-Sun comets are highly localized in space, and thus, a true correlation between near-Sun cometary perihelia and STEREO A (or B) nanodust fluxes would require a demonstration that the electromagnetically dominated trajectories of nanodust grains released from a given comet intersected the position of either STEREO spacecraft. A modeling framework such as that developed here for this study could in fact be straightforwardly applied to a study of the dynamics of nanodust released from inner heliospheric comets, an investigation identified for future work.

An additional reason by which our model may not be able to fully reproduce the STEREO observations of nanodust fluxes may be due to the accuracy of WSA-Enlil in modeling the solar wind conditions for each given CR period, which in turn is dependent on the accuracy of the input synoptic photospheric magnetic field maps that are used to drive the simulations. Despite these known limitations, we are hesitant to ascribe the majority of the model-data disagreement to this reason. Even if WSA-Enlil does not capture the full details of the three-dimensional structure of the inner heliosphere, we believe that the heliospheric fields (and their impact on nanodust grain dynamics) do not so radically change from one CR to the next, particularly during this quiescent part of the solar cycle that we have examined, that this alone could explain the variations seen in the nanodust impact rates on STEREO A and B (e.g., Zaslavsky et al., 2012). In particular, the solar photospheric observations and calculations of the potential field source surface did not rapidly change from one CR to the next during this period. We do note, however, that we have chosen here not to include solar flares or CMEs, which have been theoretically shown to dramatically alter the trajectories and resultant fluxes of nanodust grains in the inner heliosphere (e.g., O'Brien et al., 2018).

Finally, as has been previously discussed (e.g., Meyer-Vernet et al., 2009; Zaslavsky et al., 2012), a contributing factor to differences between the STEREO A and STEREO B impact count rates is likely the different geometry of the S/WAVES antennas between the two spacecraft (see e.g., Figure 11, Meyer-Vernet & Zaslavsky, 2012). In particular, the arrangement of the WAVES booms with respect to the spacecraft body, the spacecraft optical shadow, and the presumed spacecraft plasma wake are different between the two spacecraft and likely all contribute to differing response functions for nanodust grain impacts. While not exploited in this study, our modeling framework could provide the three-dimensional velocity distributions of nanodust grains at 1 au (or anywhere else within the modeling domain). Similar to recent laboratory investigations that have utilized a scaled-down replica of the Cassini spacecraft (Nouzák et al., 2018, 2020; Ye et al., 2019), one could envision laboratory studies with a scaled STEREO model that could quantify the varying response of the WAVES antennas as a function of impact location (see also the modeling study of O'Shea et al., 2017). Finally, the continued mismatch between models and the S/WAVES nanodust fluxes strongly motivates a need for improved and dedicated in situ instrumentation for nanodust grains, prototypes of which have been developed in the laboratory (O'Brien et al., 2014, 2015).

Data Availability Statement

The STEREO S/WAVES hit rate data and select model results are available online (at https://doi.org/10. 6078/D1Z70C).

References

- Andersson, L., Weber, T. D., Malaspina, D., Crary, F., Ergun, R. E., Delory, G. T., et al. (2015). Dust observations at orbital altitudes surrounding Mars. *Science*, *350*(6261). https://doi.org/10.1126/science.aad0398
- Arge, C. N., Luhmann, J. G., Odstrcil, D., Schijver, C. J., & Li, Y. (2004). Stream structure and coronal sources of the solar wind during the May 12th, 1997 CME. Journal of Atmospheric and Solar-Terrestrial Physics, 66, 1295–1309.
- Arge, C. N., & Pizzo, V. J. (2000). Improvement in the prediction of solar wind conditions using near-real time solar magnetic field updates. *Journal of Geophysical Research*, 105, 10,465–10,479.
- Baguhl, M., Grün, E., Linkert, G., Linkert, D., & Siddique, N. (1993). Identification of "small" dust impacts in the Ulysses dust detector data. Planetary and Space Science, 41(11/12), 1085–1098.

Bale, S. D., Ullrich, R., Goetz, K., Alster, N., Cecconi, B., Dekkali, M., et al. (2008). The electric antennas for the STEREO/WAVES experiment. *Space Science Reviews*, *136*(1–4). https://doi.org/10.1007/s11214-007-9251-x

Borkowski, K. J., & Dwek, E. (1995). The fragmentation and vaporization of dust in grain-grain collisions. *Astrophysical Journal*, 454, 254–276.

Acknowledgments

The authors gratefully acknowledge support from NASA's Heliophysics Supporting Research program, grant #80NSSC19K0830. The authors thank S. D. Bale and M. Pulupa for helpful conversations regarding STEREO and A. Zaslavsky for providing STEREO WAVES TDS hit rates. The authors also thank the staff at the NASA CCMC for assistance in running WSA-Enlil models and obtaining output.

Bougeret, J. L., Goetz, K., Kaiser, M. L., Bale, S. D., Kellogg, P. J., Maksimovic, M., et al. (2008). S/WAVES: The radio and plasma wave investigation on the STEREO mission. Space Science Reviews, 136(1–4). https://doi.org/10.1007/s11214-007-9298-8

Burns, J. A., Lamy, P. L., & Soter, S. (1979). Radiation forces on small particles in the solar system. Icarus, 40, 1-48.

Chow, V. W., Mendis, D. A., & Rosenberg, M. (1993). Role of grain size and particle velocity distribution in secondary electron emission in space plasmas. *Journal of Geophysical Research*, 98(A11), 19,065–19,076.

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

Czechowski, A., & Kleimann, J. (2017). Nanodust dynamics during a coronal mass ejection. Annales Geophysicae, 35, 1033–1049. https://doi.org/10.5194/angeo-35-1033-2017

Czechowski, A., & Mann, I. (2010). Formation and acceleration of nano dust in the inner heliosphere. *Astrophysical Journal*, 714, 89–99. https://doi.org/10.1088/0004-637X/714/1/89

Czechowski, A., & Mann, I. (2012). Nanodust dynamics in interplanetary space. In I. Mann, N. Meyer-Vernet, A. Czechowski (Eds.), Nanodust in the solar system: Discoveries and interpretations, astrophysics and space science library (Vol. 385). Berlin, Heidelberg: Springer-Verlag.

Dohnanyi, J. S. (1969). Collisional model of asteroids and their debris. Journal of Geophysical Research, 74(10), 2531–2554.

Draine, B. T., & Salpeter, E. E. (1979). On the physics of dust grains in hot gas. Astrophysical Journal, 231, 77–94. https://doi.org/10.1086/157165

Dzhanoev, A. R., Schmidt, J., Liu, X., & Spahn, F. (2016). Charging of small grains in a space plasma: Application to Jovian stream particles. *Astronomy & Astrophysics*, 591, A147. https://doi.org/10.1051/0004-6361/201527891

Fränz, M., & Harper, D. (2002). Heliospheric coordinate systems. Planetary and Space Science, 50, 217-233.

Gáspár, A., Psaltis, D., Özel, F., Rieke, G. H., & Cooney, A. (2012). Modeling collisional cascades in debris disks: The numerical method. Astrophysical Journal, 749, 14.

Gosling, J. T., & Pizzo, V. J. (1999). Formation and evolution of corotating interaction regions and their three dimensional structure. Space Science Reviews, 89, 21–52.

Granvik, M., Morbidelli, A., Jedicke, R., Bolin, B., Bottke, W. F., Beshore, E., et al. (2016). Super-catastrophic disruption of asteroids at small perihelion distances. *Nature*, 530, 303–306. https://doi.org/10.1038/nature16934

Graps, A. L., Grün, E., Svedhem, H., Krüger, H., Horányi, M., Heck, A., & Lammers, S. (2000). Io as the source of the Jovian dust streams. *Nature*, 405, 48–50.

Greenberg, R. (1982). Orbital interactions: A new geometrical formalism. Astronomical Journal, 87, 184–195.

Grün, E., Baguhl, M., Hamilton, D. P., Riemann, R., Zook, H. A., Dermott, S., et al. (1996). Constraints from Galileo observations on the origin of Jovian dust streams. *Nature*, 381, 395–398.

Grün, E., Zook, H. A., Baguhl, M., Balogh, A., Bame, S. J., Fechtig, H., et al. (1993). Discovery of Jovian dust streams and interstellar grains by the Ulysses spacecraft. *Nature*, *362*, 428–430.

Grün, E., Zook, H. A., Fechtig, H., & Giese, R. H. (1985). Collisional balance of the meteoric complex. Icarus, 62, 244-272.

Gurnett, D. A., Ansher, J. A., Kurth, W. S., & Granroth, L. J. (1997). Micron-sized dust particles detected in the outer solar system by the Voyager 1 and 2 plasma wave instruments. *Geophysical Research Letters*, 24(24), 3125–3128.

Hoeksema, J. T. (1995). The large-scale structure of the heliospheric current sheet during the Ulysses epoch. *Space Science Reviews*, 72, 137–148.

Horányi, M. (1996). Charged dust dynamics in the solar system. Annual Review of Astronomy and Astrophysics, 34, 383-418.

Horányi, M., Burns, J. A., & Hamilton, D. P. (1992). The dynamics of Saturn's E ring particles. *Icarus*, 97, 248–259.

Horányi, M., Grün, E., & Heck, A. (1997). Modeling the Galileo dust measurements at Jupiter. *Geophysical Research Letters*, 24(17), 2175–2178.

Horányi, M., Juhász, A., & Morfill, G. E. (2008). Large-scale structure of Saturn's E-ring. *Journal of Geophysical Research*, 35, L04203. https://doi.org/10.1029/2007GL032726

Horányi, M., Morfill, G., & Grün, E. (1993). The dusty ballerina skirt of Jupiter. Journal of Geophysical Research, 98(A12), 21,245–21,251.
Horányi, M., Robertson, S., & Walch, B. (1995). Electrostatic charging properties of simulated lunar dust. Geophysical Research Letters, 22(16), 2079–2082.

Horányi, M., Szalay, J. R., Kempf, S., Schmidt, J., Grün, E., Srama, R., & Sternovsky, Z. (2015). A permanent, asymmetric dust cloud around the Moon. *Nature*, 522, 324–326. https://doi.org/10.1038/nature14479

Horányi, M., Walch, B., Robertson, S., & Alexander, D. (1998). Electrostatic charging properties of Apollo 17 lunar dust. *Journal of Geophysical Research*, 103(E4), 8575–8580.

Hsu, H.-W., Kempf, S., & Jackman, C. M. (2010). Observation of Saturnian stream particles in the interplanetary space. *Icarus*, 206, 653–661.

Hsu, H.-W., Kempf, S., Postberg, F., Trieloff, M., Burton, M., Roy, M., et al. (2011). Cassini dust stream particle measurements during the first three orbits at Saturn. *Journal of Geophysical Research*, *116*, A08213. https://doi.org/10.1029/2010JA015959

Hsu, H.-W., Postberg, F., Kempf, S., Trieloff, M., Burton, M., Roy, M., et al. (2011). Stream particles as the probe of the

dust-plasma-magnetosphere interaction at Saturn. *Journal of Geophysical Research*, *116*, A09215. https://doi.org/10.1029/2011JA016488 Hundhausen, A. J. (1973). Nonlinear model of high-speed solar wind streams. *Journal of Geophysical Research*, *78*(10), 1528–1542.

Ip, W.-H., & Yan, T.-H. (2012). Injection and acceleration of charged nano-dust particles from sungrazing comets, *Physics of the heliosphere: A 10 year retrospective* (Vol. 1436, pp. 30–35). Melville, NY: American Institute of Physics. https://doi.org/10.1063/1.4723586

Janches, D., Heinselman, C. J., Chau, J. L., Chandran, A., & Woodman, R. (2006). Modeling the global micrometeor input function in the upper atmosphere observed by high power and large aperture radars. *Journal of Geophysical Research*, *111*, A07317. https://doi.org/10. 1029/2006JA011628

Jia, Y.-D., Ma, Y. J., Russell, C. T., Lai, H. R., Toth, G., & Gombosi, T. I. (2012). Perpendicular flow deviation in a magnetized counter-streaming plasma. *Icarus*, 218, 895–905. https://doi.org/10.1016/j.icarus.2012.01.017

Jian, L. K., MacNeice, P. J., Taktakishvili, A., Odstrcil, D., Jackson, B., Yu, H.-S., et al. (2015). Validation for solar wind prediction at Earth: Comparison of coronal and heliospheric models installed at the CCMC. *Space Weather*, *13*, 316–338.

Jones, G. H., Knight, M. M., Battams, K., Boice, D. C., Brown, J., Giordano, S., et al. (2018). The science of sungrazers, sunskirters, and other near-Sun comets. *Space Science Reviews*, 214, 86.

Juhász, A., & Horányi, M. (2013). Dynamics and distribution of nano-dust particles in the inner solar system. *Geophysical Research Letters*, 40, 2500–2504. https://doi.org/10.1002/grl.50535

Kaiser, M. L., Kucera, T. A., Davila, J. M., St. Cyr, O. C., Guhathakurta, M., & Christian, E. (2008). The STEREO mission: An introduction. Space Science Reviews, 136, 5–16. https://doi.org/10.1007/s11214-007-9277-0

Kellogg, P. J. (2017). Note on the Pantellini et al. process for dust impact signals on spacecraft. Journal of Geophysical Research: Space Physics, 122, 63–70. https://doi.org/10.1002/2016JA023073

- Kellogg, P. J., Goetz, K., & Monson, S. J. (2016). Dust impact signals on the Wind spacecraft. Journal of Geophysical Research: Space Physics, 121, 966–991. https://doi.org/10.1002/2015JA021124
- Kellogg, P. J., Goetz, K., & Monson, S. J. (2018). Are STEREO single hits dust impacts. Journal of Geophysical Research: Space Physics, 123, 7211–7219. https://doi.org/10.1029/2018JA025554
- Kempf, S., Srama, R., Horányi, M., Burton, M., Helfert, S., Moragas-Klostermeyer, G., et al. (2005). High-velocity streams of dust originating from Saturn. *Nature*, 433, 289–291.
- Kessler, D. J. (1981). Derivation of the collision probability between orbiting bodies: The lifetimes of Jupiter's outer moons. *Icarus*, 48, 39–48.
- King, J. H., & Papitashvili, N. E. (2005). Solar wind spatial scales in and comparisons of hourly Wind and ACE plasma and magnetic field data. Journal of Geophysical Research, 110, A02104. https://doi.org/10.1029/2004JA010649
- Kobayashi, H., Watanabe, S., Kimura, H., & Yamamoto, T. (2009). Dust ring formation due to sublimation of dust grains drifting radially inward by the Poynting-Robertson drag: An analytical model. *Icarus*, 201, 395–405.
- Krüger, H., Horányi, M., & Grün, E. (2003). Jovian dust streams: Probes of the Io plasma torus. Geophysical Research Letters, 30(2), 1058. https://doi.org/10.1029/2002GL015920
- Kurth, W. S., Averkamp, T. F., Gurnett, D. A., & Wang, Z. (2006). Cassini RPWS observations of dust in Saturn's E ring. Planetary and Space Science, 54(9-10), 988–998. https://doi.org/10.1016/j.pss.2006.05.011
- Lai, H. R., & Russell, C. T. (2018). Nanodust released in interplanetary collisions. Planetary and Space Science, 156, 2–6. https://doi.org/ 10.1016/j.pss.2017.10.003
- Lai, H. R., Russell, C. T., Jia, Y. D., Wei, H. Y., & Angelopoulos, V. (2015). Momentum transfer from solar wind to interplanetary field enhancements inferred from magnetic field draping signatures. *Geophysical Research Letters*, 42, 1640–1645. https://doi.org/10.1002/ 2015GL063302
- Le Chat, G., Issautier, K., Zaslavsky, A., Pantellini, F., Meyer-Vernet, N., Belheouane, S., & Maksimovic, M. (2015). Effect of the interplanetary medium on nanodust observations by the solar terrestrial relations observatory. *Solar Physics, 290*, 933–942.
- Lee, C. O., Luhmann, J. G., Hoeksema, J. T., Sun, X., Arge, C. N., & de Pater, I. (2011). Coronal field opens at lower height during the solar cycles 22 and 23 minimum periods: IMF comparison suggests the source surface should be lowered. *Solar Physics*, 269, 367–388. https://doi.org/10.1007/s11207-010-9699-9
- Lee, C. O., Luhmann, J. G., Odstrcil, D., MacNeice, P. J., de Pater, I., Riley, P., & Arge, C. N. (2009). The solar wind at 1 AU during the declining phase of solar cycle 23: Comparison of 3-D numerical model results with observations. *Solar Physics*, 254, 155–183.
- Leinert, C., Link, H., Pitz, E., & Giese, R. H. (1976). Interpretation of a rocket photometry of the inner zodiacal light. Astronomy & Astrophysics, 47, 221–230.

Leinert, C., Richter, I., Pitz, E., & Planck, B. (1981). The zodiacal light from 1.0 to 0.3 AU. Astronomy & Astrophysics, 103, 177-188. Lhotka, C., Bourdin, P., & Narita, Y. (2016). Charged dust grain dynamics subject to solar wind, Poynting-Robertson drag, and the

interplanetary magnetic field. Astrophysical Journal, 828(10), 1–10.

Löhne, T., Krivov, A. V., & Rodmann, J. (2008). Long-term collisional evolution of debris disks. Astrophysical Journal, 673, 1123–1127. https://doi.org/10.1086/524840

- MacNeice, P. (2009a). Validation of community models: Identifying events in space weather model timelines. *Space Weather*, 7, S06004. https://doi.org/10.1029/2009SW000463
- MacNeice, P (2009b). Validation of community models: 2. Development of a baseline using the Wang-Sheeley-Arge model. *Space Weather*, 7, S12002. https://doi.org/10.1029/2009SW000489
- MacNeice, P., Jian, L. K., Antiochos, S. K., Arge, C. N., Bussy-Virat, C. D., DeRosa, M. L., et al. (2018). Assessing the quality of models of the ambient solar wind. *Space Weather*, *16*, 1644–1667. https://doi.org/10.1029/2018SW002040
- Maksimovic, M., Gary, S. P., & Skoug, R. M. (2000). Solar wind electron suprathermal strength and temperature gradients: Ulysses observations. Journal of Geophysical Research, 105(A8), 18,337–18,350.
- Malaspina, D. M., Horányi, M., Zaslavsky, A., Goetz, K., Wilson, L. B. III, & Kersten, K. (2014). Interplanetary and interstellar dust observed by the Wind/WAVES electric field instrument. *Geophysical Research Letters*, 41, 266–272. https://doi.org/10.1002/2013GL058786
- Malaspina, D. M., O'brien, L. E., Thayer, F., Sternovsky, Z., & Collette, A. (2015). Revisiting STEREO interplanetary and interstellar dust flux and mass estimates. *Journal of Geophysical Research: Space Physics*, 120, 6085–6100. https://doi.org/10.1002/2015JA021352
- Malaspina, D. M., Szalay, J. R., Pokorný, P., Page, B., Bale, S. D., Bonnell, J. W., et al. (2020). In situ observations of interplanetary dust variability in the inner heliosphere. *Astrophysical Journal*, *892*, 9. https://doi.org/10.3847/1538-4357/ab799b
- Malaspina, D. M., & Wilson, L. B. III (2016). A database of interplanetary and interstellar dust detected by the Wind spacecraft. Journal of Geophysical Research: Space Physics, 121, 9369–9377. https://doi.org/10.1002/2016JA023209
- Marsch, E., Pilipp, W. G., Thieme, K. M., & Rosenbauer, H. (1989). Cooling of solar wind electrons inside 0.3 AU. Journal of Geophysical Research, 94(A6), 6893–6898.
- McBride, N., & McDonnell, J. A. M. (1999). Meteoroid impacts on spacecraft: Sporadics, streams, and the 1999 Leonids. *Planetary and Space Science*, 47, 1005–1013.
- Merson, R. H. (1975). Numerical integration of the differential equations of celestial mechanics (*Tech. Rep. 74184*). Hants, U. K.: Royal Aircraft Establishment.
- Meyer-Vernet, N., Lecacheux, A., Kaiser, M. L., & Gurnett, D. A. (2009). Detecting nanoparticles at radio frequencies: Jovian dust stream impacts on Cassini/RPWS. *Geophysical Research Letters*, 36, L03103. https://doi.org/10.1029/2008GL036752
- Meyer-Vernet, N., & Zaslavsky, A. (2012). In situ detection of interplanetary and Jovian nanodust with radio and plasma wave instruments. In I. Mann, N. Meyer-Vernet, A. Czechowski (Eds.), *Nanodust in the solar system: Discoveries and interpretations, astrophysics and space science library* (Vol. 385, pp. 133–160). Berlin, Heidelberg: Springer.
- Mozer, F. S., Agapitov, O. V., Bale, S. D., Bonnell, J. W., Goetz, K., Goodrich, K. A., et al. (2020). Time domain structures and dust in the solar vicinity: Parker Solar Probe observations. Astrophysical Journal Supplement Series, 246(50), 1–5. https://doi.org/10.3847/1538-4365/ab5e4b
- Mukai, T., & Schwehm, G. (1981). Interaction of grains with the solar energetic particles. Astronomy & Astrophysics, 95, 373-382.
- Nouzák, L., Hsu, S., Malaspina, D., Thayer, F. M., Ye, S.-Y., Pavlu, J., et al. (2018). Laboratory modeling dust impact detection by the Cassini spacecraft. *Planetary and Space Science*, *156*, 85–91.
- Nouzák, L., Sternovsky, Z., Horányi, M., Hsu, S., Pavlu, J., Shen, M.-H., & Ye, S.-Y. (2020). Magnetic field effect on antenna signals induced by dust particle impacts. *Journal of Geophysical Research: Space Physics*, *125*, e2019JA027245. https://doi.org/10.1029/2019JA027245

- O'Brien, L., Auer, S., Gemer, A., Grün, E., Horányi, M., Juhász, A., et al. (2014). Development of the nano-dust analyzer (NDA) for detection and compositional analysis of nanometer-size dust particles originating from the inner heliosphere. *Review of Scientific Instruments*, *85*, 35113.
- O'Brien, D. P., & Greenberg, R. (2005). The collisional and dynamical evolution of the main-belt and NEA size distributions. *Icarus*, 178, 179–212.
- O'Brien, L., Grün, E., & Sternovsky, Z. (2015). Optimization of the Nano-Dust Analyzer (NDA) for operation under solar UV illumination. *Planetary and Space Science*, 119, 173–180. https://doi.org/10.1016/j.pss.2015.09.014
- O'Brien, L., Juhász, A., Sternovsky, Z., & Horányi, M. (2018). Effects of interplanetary coronal mass ejections on the transport of nano-dust generated in the inner solar system. *Planetary and Space Science*, 156, 7–16. https://doi.org/10.1016/j.pss.2017.11.013
- O'Shea, E., Sternovsky, Z., & Malaspina, D. M. (2017). Interpreting dust impact signals detected by the STEREO spacecraft. *Journal of Geophysical Research: Space Physics*, 122, 11,864–11,873. https://doi.org/10.1002/2017JA024786
- Odstrcil, D. (2003). Modeling 3D solar wind structure. Advances in Space Research, 32, 497-506.
- Öpik, E. J. (1951). Collision probabilities with the planets and the distributions of interplanetary matter. *Proceedings of the Royal Irish Academy, Section A*, 54, 164–199.
- Page, B., Bale, S. D., Bonnell, J. W., Goetz, K., Goodrich, K., Harvey, P. R., et al. (2020). Examining dust directionality with the Parker Solar Probe FIELDS instrument. Astrophysical Journal Supplement Series, 246(51), 13. https://doi.org/10.3847/1538-4365/ab5f6a
- Pan, M., & Schlichting, H. E. (2012). Self-consistent size and velocity distributions of collisional cascades. Astrophysical Journal, 747, 113. https://doi.org/10.1088/0004-637X/747/2/113
- Pantellini, F., Belheouane, S., Meyer-Vernet, N., & Zaslavsky, A. (2012). Nano dust impacts on spacecraft and boom antenna charging. Astrophysical Space Science, 341, 309–314. https://doi.org/10.1007/s10509-012-1108-4

Parker, E. N. (1958). Dynamics of the interplanetary gas and magnetic fields. Astrophysical Journal, 128, 664-676.

- Pilipp, W. G., Miggenrieder, H., Mühlhäuser, K.-H., Rosenbauer, H., & Schwenn, R. (1990). Large-scale variations of thermal electron parameters in the solar wind between 0.3 and 1.0 AU. *Journal of Geophysical Research*, *95*(A5), 6305–6329.
- Piquette, M., & Horányi, M. (2017). The effect of asymmetric surface topography on dust dynamics on airless bodies. *Icarus*, 291, 65–74. https://doi.org/10.1016/j.icarus.2017.03.019
- Poppe, A. R. (2016). An improved model for interplanetary dust fluxes in the outer solar system. *Icarus*, 264, 369–386.
- Poppe, A. R. (2019). The contribution of Centaur-emitted dust to the interplanetary dust distribution. Monthly Notices of the Royal Astronomical Society, 490, 2421–2429. https://doi.org/10.1093/mnras/stz2800
- Poppe, A., & Horányi, M. (2010). Simulations of the photoelectron sheath and dust levitation on the lunar surface. *Journal of Geophysical Research*, 115, A08106. https://doi.org/10.1029/2010JA015286
- Poppe, A., James, D., & Horányi, M. (2011). Measurements of the terrestrial dust influx variability by the Cosmic Dust Experiment. *Planetary and Space Science*, 59, 319–326.
- Poppe, A. R., Piquette, M., Likhanskii, A., & Horányi, M. (2012). The effect of surface topography on the lunar photoelectron sheath and electrostatic dust transport. *Icarus*, 221, 135–146.

Rasca, A. O., Horányi, M., Oran, R., & van der Holst, B. (2014). Modeling solar wind mass-loading in the vicinity of the Sun using 3-D MHD simulations. Journal of Geophysical Research: Space Physics, 119, 18–25. https://doi.org/10.1002/2013JA019365

- Rasca, A. P., Oran, R., & Horányi, M. (2014). Mass loading of the solar wind by a sungrazing comet. *Geophysical Research Letters*, 41, 5376–5381. https://doi.org/10.1002/2014GL060990
- Sittler, E. C. Jr., & Scudder, J. D. (1980). An empirical polytrope law for solar wind thermal electrons between 0.45 and 4.76 AU: Voyager 2 and mariner 10. Journal of Geophysical Research, 85(A10), 5131–5137.
- Stark, C. C., & Kuchner, M. J. (2009). A new algorithm for self-consistent three-dimensional modeling of collisions in dust debris disks. Astrophysical Journal, 707, 543–553.
- Sternglass, E. J. (1954). The theory of secondary emission (Tech. Rep. Sci. Pap. 1772). Pittsburgh, PA: Westinghouse Res. Lab.
- Sternovsky, Z., Chamberlin, P., Horányi, M., Robertson, S., & Wang, X. (2008). Variability of the lunar photoelectron sheath and dust mobility due to solar activity. *Journal of Geophysical Research*, *113*, A10104. https://doi.org/10.1029/2008JA013487
- Suess, S. T., McComas, D. J., & Hoeksema, J. T. (1993). Prediction of the heliospheric current sheet tilt: 1992–1996. Geophysical Research Letters, 20(3), 161–164.
- Szalay, J. R., Pokorný, P., Bale, S. D., Christian, E. R., Goetz, K., Goodrich, K., et al. (2020). The near-Sun dust environment: Initial observations from Parker Solar Probe. Astrophysical Journal Supplement Series, 246(27), 12. https://doi.org/10.3847/1538-4365/ab50c1
- Ulrich, R. K., Evans, S., Boyden, J. E., & Webster, L. (2002). Mount Wilson synoptic magnetic fields: Improved instrumentation, calibration, and analysis applied to the 2000 July 14 flare and to the evolution of the dipole field. *Astronomy and Astrophysics Supplement Series*, 139, 259–279.
- Walch, B., Horányi, M., & Robertson, S. (1995). Charging of dust grains in plasma with energetic electrons. *Physical Review Letters*, 75(5), 838–842.
- Wang, Z. (2004). Interplanetary dust particles detected by the Voyager 1 and 2 Plasma Wave instruments (Master's thesis), University of Iowa.
- Wang, Z., Gurnett, D. A., Averkamp, T. F., Persoon, A. M., & Kurth, W. S. (2006). Characteristics of dust particles detected near Saturn's ring plane with the Cassini Radio and Plasma Wave instrument. *Planetary and Space Science*, 54(9–10), 957–966. https://doi.org/10. 1016/j.pss.2006.05.015
- Wehry, A., & Mann, I. (1999). Identification of β -meteoroids from measurements of the dust detector onboard the Ulysses spacecraft. Astronomy & Astrophysics, 341, 296–303.
- Wetherill, G. W. (1967). Collisions in the asteroid belt. Journal of Geophysical Research, 72, 2429-2444.
- Wood, S. R., Malaspina, D. M., Andersson, L., & Horányi, M. (2015). Hypervelocity dust impacts on the Wind spacecraft: Correlations between Ulysses and Wind interstellar dust detections. *Journal of Geophysical Research: Space Physics*, 120, 7121–7129. https://doi.org/ 10.1002/2015JA021463
- Ye, S.-Y., Vaverka, J., Nouzak, L., Sternovsky, Z., Zaslavsky, A., Pavlu, J., et al. (2019). Understanding Cassini RPWS antenna signals triggered by dust impacts. *Geophysical Research Letters*, *46*, 10,941–10,950. https://doi.org/10.1029/2019GL084150
- Zaslavsky, A., Meyer-Vernet, N., Mann, I., Czechowski, A., Issautier, K., Le chat, G., et al. (2012). Interplanetary dust detection by radio antennas: Mass calibration and fluxes measured by STEREO/WAVES. *Journal of Geophysical Research*, 117, A05102. https://doi.org/10. 1029/2011JA017480
- Zook, H. A., & Berg, O. E. (1975). A source for hyperbolic cosmic dust particles. Planetary and Space Science, 23, 183-203.
- Zook, H. A., Grün, E., Baguhl, M., Hamilton, D. P., Linkert, G., Liou, J.-C., et al. (1996). Solar wind magnetic field bending of Jovian dust trajectories. *Science*, 274(5292), 1501–1503.