Comets as a Possible Source of Nanodust in the Solar System Cloud and in Planetary Debris Discs

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Summary

Comets, comet-like objects and their fragments are the most plausible source both for the dust in the inner heliosphere and in planetary debris discs around other stars. The smallest size of dust particles in debris disks is not known and recent observational results suggest that the size distribution of the dust extends down to sizes of few nm or few 10 nm. In the solar system, electric field measurements from spacecraft observe events that are explained with high-velocity impacts of nm-sized dust. In some planetary debris discs an observed mid to near infrared emission supposedly results from hot dust located in the vicinity of the star. And the observed emission is characteristic of dust sizes few 10 nm. Rosetta observations, on the other side provide little information on the presence of nanodust near comet 67P/Churyumov-Gerasimenko. This article describes why this is not in contradiction to the observations of nanodust in the heliosphere and in planetary debris discs. The direct ejection of nanodust from the nucleus of the comet would not contribute significantly to the observed nanodust fluxes. We discuss a scenario that nanodust forms in the interplanetary dust cloud through the high velocity collision process in the interplanetary medium for which the production rates are highest near the Sun. Likewise fragmentation by collisions occurs near the star in planetary debris discs. The collisional fragmentation process in the inner solar system occurs at similar velocities as the collisional evolution in the interstellar medium does. Ä question to the future studies is whether there is a common magic size of the smallest collision fragments and what determines this size.

Introduction

Comets are one of the major sources of the solar systems interplanetary dust cloud. This solar system debris disc is observed with in-situ measurements from spacecraft and in the Zodiacal light. Astronomical observations describe the dust spatial distribution and basic optical properties [1] in the size interval several 100 nm to several 10 μm. Smaller dust is observed in-situ from spacecraft and contains also a component of interstellar dust that streams into the solar system [see e.g. 2]. The interplanetary dust cloud has the highest number density in the inner heliosphere, near the ecliptic inside about 3 au from the Sun. The solar system dust originates primarily from asteroids and comets and different estimates vary between >70% from asteroids and 75% from comets [3]. A plausible source of dust inside 1 au are comets, their fragments, and the dust particles that are generated by dust-dust collisions. Since dust fluxes increase toward the Sun, collision rates are high and dust production rates are large there [4,5]. Basic considerations suggest that if fragments of about 10 nm and smaller form, then they can be carried with the solar wind [6]. This hypothesized nanodust can reach a speed of the order of solar wind speed [7]. Events that are explained with impacts of fast nanodust onto spacecraft were discovered with STEREO, they are measured with electric antennas at 1 au [8]. Cassini detected impacts at larger distance from the Sun. Still the question remains how nm-sized fragments form in the collision process [3]. The evolution of the interplanetary dust cloud may serve as an example for the evolution also of planetary debris discs [9]. This paper describes some recent findings on nanodust in the inner heliosphere and in planetary debris discs, addresses the question what we can derive from Rosetta results about the existence of nm-sized cometary dust and discusses why Rosetta provides only little direct observational results on nanodust. Perspectives are shown to study nanodust in future and to observe nanodust with upcoming space missions.

In-situ Measurements

Dust with sizes smaller ~µm is typically observed with in-situ measurements and for instance the Ulysses dust instrument that explored the solar system dust cloud during two solar cycles covered the sizes of few 10 nm to few µm [2, 10]. Dust particles are also observed with electric field measurements because the impact process generates transient plasma cloudlets that influence, e.g. the measured spacecraft potential. The STEREO plasma wave instrument discovered nanodust with sizes presumably few nm near 1 au and this detection was possible because the impact speeds are high and therefore the nanodust impacts generate comparatively large signals [8]. A number of detailed studies were carried out related to the STEREO observations of nm-sized and larger dust near 1 au [11, 12, 13, 14, 15, 16, 17]. The detection process was described and studied in detail [18] also pointing out some still open questions. In fact, it is intriguing that in spite of large time variations in the observed fluxes the average fluxes fit well to an extrapolation of the empirical interplanetary dust flux model [19] to smaller sizes (see Figure 1). For Cassini, an analysis of the plasma wave data during Cassini cruise toward Jupiter was made only during parts of the orbit in order to avoid possibly occurring instrumental effects, still it provided data on nanodust fluxes at different distances from the Sun. The observed fluxes were found to be consistent with the assumption that the majority of the nanodust originate from the vicinity of the Sun and then are accelerated in the solar wind [20].

Nanodust in the heliosphere near the Sun

The interplanetary dust cloud develops through mutual dust collisions and sub-µm sized fragments are typically in unbound orbits. Collision rates and dust production rates per volume in space increase toward the Sun and sub-µm collision fragments are ejected by radiation pressure, by electromagnetic force and by a combination of both. The surface-charge-to-mass ratio of the dust increases with decreasing dust size so that dust particles of sizes few nm ("nanodust") are strongly influenced by electromagnetic forces. They are deflected in the solar wind in a way that is similar to the pick-up of heavy ions and they finally reach solar wind speed [7, 21]. Calculations of nanodust trajectories near the Sun [7] also showed that the nanodust – under certain conditions - is trapped within approximately 0.2 to 0.3 au for some time before it is deflected outward. In a simple picture, based on the guiding centre approximation this can be described as the sliding of dust particles (represented by the guiding centre) along the rotating solar magnetic field line. In this simplified view (Figure 2) the sliding along the field line is determined by the combination of the magnetic mirror force, the solar gravity and a term in the equation of motion acting as a centrifugal force [21]. The trapping ends when the nanodust sublimates close to the Sun or when it is ejected outward because the centrifugal force term becomes predominant. Trapping only occurs under certain initial orbital conditions and trapping conditions depend on a number of different parameters so that it is plausible that the nanodust flux outward varies in time [7, 21]. The dust flux can vary also due to other effects, like, e.g. the influence of the solar magnetic field structure [22]. It was however, not possible so far to determine what is the major cause of observed time variations and to trace the nanodust flux back to its source [12, 20, 21, 22]. Models so far were based on the assumption that this nanodust is produced by mutual collisions in the interplanetary dust cloud [7, 8, 12, 13, 14, 21, 22]. The most plausible source of dust in the inner heliosphere inside 1 au are comets and their fragments.

Hot debris discs – nanodust in the vicinity of a star

Dust in the inner heliosphere bears a similarity to the inner circum-stellar debris discs [cf. 23] ("hot debris discs"). The debris dust discs are produced from planetesimals in a similar way as asteroids and comets produce the interplanetary dust. The relatively "cool" dust in the discs produces thermal emission that is observed in mid-infrared because at this spectral range the dust emission exceeds the stellar brightness. The "cool dust" is located at several 10 to 100 au from the stars and in a region that is comparable to the solar system's Kuiper belt. The debris discs are produced by planetesimals and dust-dust collisions. Since debris discs possibly contain planets, knowing debris discs and their dynamics is important for understanding in general the extrasolar planetary systems [24]. Some of the debris discs display also mid and near infrared emissions that point to the existence of warm dust that is located closer to the star [24, 26, 27, 28].

Dust is ejected outward from the star by radiation pressure force. The ejected dust stirs the collisional evolution in the debris disc at larger distances from the stars [24, 25]. Hence, understanding this inner dust component is important for understanding the system as a whole. The inner debris disc brightness needs to be characterised also when planning future imaging observations of extrasolar earth-like planets [24]. In their recent study Absil et al. [24] identify 11 debris discs around main sequence stars that have a near infrared excess "probably associated with hot circumstellar dust". Attempts to explain that a sufficient number of dust particles is kept so close to the star in spite of the ejection by radiation pressure discuss the braking due to a gas component [28] or trapping due to electromagnetic forces [26] similar to the trapping of nanodust near the Sun. A pile-up zone [31] similar to models of dust rings near the Sun [32] was also considered. The pile-up results from the dust sublimation near the Sun and the size dependence of Poynting-Robertson drag. But the increase in dust number density that is caused by this process is small and limited to a narrow region [5]. Some observational results support the hypothesis that the inner warm dust component is made up of nanodust. Nanodust has a characteristic emission spectrum [cf. 29, 30] and characteristic small particle effects are seen in some of the observed emission spectra. The Fomalhaut inner debris disc brightness for instance, can be described with a dust model that includes 10 nm to 0.5 μm sized dust at ≈ 0.1 - 0.3 au from the star [28]. A nanodust emission model can also explain the observations at Vega (see Figure 3). The observed spectral characteristics make the nanodust a good candidate for explaining the observations. A plausible source of the nanodust are comet-like objects and their fragments and this brings up the question whether there is evidence for nanodust in the vicinity of comets or for nanodust being formed from fragmentation of cometary dust.

Evidence for nanodust from comets

Before in-situ measurements discovered nanodust in the vicinity of planets and in the interplanetary medium some detections were reported from the space missions to 1P/Halley. Three spacecraft crossed the path of the comet with relative velocity 78 km/s for Vega 1 and 2 and 70 km/s for Giotto and at flyby distances 8 890 km for Vega 1, 8 030 km for Vega 2 and 596 km for Giotto. The dust impact ionization instruments on-board detected a large number of unexpected signals, presumably caused by impacts of dust with masses of the order 10^{-21} kg [33]. This nanodust ranges over larges distances up to 730 000 km and makes up up to 6 % of the mass loss that is derived from the dust data. This nanodust possibly forms at some distance from the nucleus by fragmentation of larger particles [34]. Some dust measurements with Stardust at Wild 2 also point to fragmentation of larger dust taking place in the comet [35]. Observations with other instruments of 1P/Halley and of C/1996 B2 Hiyakutake at distance several 1000 km and beyond were explained with dust fragmentation, or some combination of fragmentation and sublimation [36, 37, 38]. A new result related to nanodust near comets comes from an analysis of x-ray observations [39] which leads the authors to the conclusion that in addition to scattering and fluorescence from gas also large dust and nanodust contribute to the x ray brightness. As discussed in a study of possible nanodust production from the nucleus of 67P/Churyumov-Gerasimenko [40] the Rosetta dust instruments are not able to detect nanodust, but there is a possibility that other instruments detect impacts of fast nanodust. Because of the small relative velocity between Rosetta and the comet, dust impacts can only be observed if the dust is sufficiently accelerated.

Several authors considered the dynamics of nm-sized dust near the comet in order to estimate its acceleration. Assuming the nanodust is directly released from the nucleus when its activity is low, the calculations show that it is immediately charged and accelerated [40], which motivated the suggestion that nanodust can be observed with particle detectors onboard Rosetta. Considering that nanodust possibly forms from fragmentation of larger dust in the coma, another test particle simulation [41] considered charged dust outside of the region where gas drag is important. The particles are launched at 150 km with three different initial velocities (50, 300, and 700 m/s) and trajectories are calculated outward to 10 000 km around the nucleus, beyond which typical solar wind conditions prevail. A quasi-neutral hybrid model of the comet interacting with the solar wind [42] describes the electric and magnetic fields. The calculations show that the nanodust is accelerated and moves in the direction of the electric field, predominantly. Assuming a dust surface potential of 5.4 Volt the 1 nm sized dust reaches final speed 74 km/s and the 10 nm dust 7.4 km/s. These calculations that assume for the Rosetta mission unperturbed solar wind conditions at 1.45 au, show that acceleration by electric force is efficient only in the small size limit. Another study of the dust dynamics applying gas-drag acceleration near the comet, as well as radiation pressure and solar wind induced electric field suggests the formation of dust plumes that intermittently sweep over the Rosetta spacecraft and that can be observed with the Ion and Electron Sensor RPC/IES [43].

Indeed, Burch et al. [44] report that RPC/IES detects negative particles at energies from about 100 eV/q to more than 18 keV/q and interpret these observations as clusters of molecules with diameters less than 100 nm; the particles reach Rosetta from two different approximate direction: from the comet and from the direction of the Sun. Hence, alternatively one could speculate that impacts from Sun direction could also come not be from nanodust, but from minor solar wind constituents, as e.g. negative oxygen ions have energy around 10 keV. Aside from directly observing nanodust, information on composition and structure of larger dust can be helpful for estimating its fragmentation behaviour. Several Rosetta instruments are designed for collecting dust for direct analysis onboard. Scales of spatial resolution are however of order 100 nm and larger. Bentley et al. [45] report from analysing dust particles with the on-board atomic force microscope instrument MIDAS that the particles are aggregates of smaller, elongated grains and presume that they were formed in slow dust growth through hierarchical agglomeration. MIDAS results show that the particles are from few tens of μm in size down to hundreds of nm and often have fractal structure with $\approx\mu$m subunits [46]. The particles have different morphological structures and some of them are very fragile [47]. Most of the dust particles that were measured with the secondary ion mass analyser COSIMA originate from the disruption of large (>1 mm) aggregates [48]. Fray et al. [49] report from the COSIMA observations that the dust contains solid (insoluble) organic matter in very large macromolecular compounds. Also, the GAIDA instrument is designed for measuring large dust, but finds some fragmentations events, presumably due to electrostatic forces that fragment aggregates [50]. One can also speculate that fragmentation occurred less often than during the encounters at 1P/Halley, because observations with Rosetta are at large distance to the Sun and fragmentation by sublimation of some of the dust compounds less likely. As in a study based on Zodiacal polarisation observations Lasue et al. [51] e.g. suggest that solid carbonaceous compounds in cometary dust progressively disappear within 1.5 and 0.5 au.

Future studies and space measurements

Considering cometary dust in order to estimate dust properties in the inner solar system dust cloud is reasonable. The most recent studies quantify the contribution from cometary dust to respectively 90 percent [52] and 60 to 80 percent [53]. It is not clear at this time, whether the ongoing analyses of Rosetta measurements will provide any further evidence for the existence of nanodust in the vicinity of the comet. Even if the direct formation of nanodust near the nucleus is not likely to be a major source of the nanodust observed in the heliosphere, an observation would help to better understand the formation process of the nanodust, since this can possibly differ from the formation of larger fragments. Based on spectral observations of NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) mission Wooden et al. [54] find nanoparticles in the Moon's exosphere that have sizes smaller than 20 to 30 nm, their amount is variable and exceeds estimates inferred from models describing impact-generated ejecta. In an earlier study of possible nanodust production at the nucleus of a comet for instance, cosmic-ray induces erosion was suggested as a process to eject nanodust from the surface of atmosphere-less solar system bodies [55]. A similar process could also occur during impact of cosmic rays onto larger dust by the token that the generated fragments are of similar size as the tunnels they form in the dust material.

For understanding what size of fragments the cometary dust generates it is helpful to find whether there is any evidence for nm sized compounds or substructures in the measured dust compositions and structures. To better understand whether fragmentation can be (instead of being caused by collisions) caused by sublimation of some of the dust compounds it would be helpful to consider whether observations indicate that large cometary fragments contain volatiles or compounds that would sublimate at few 100 K temperatures in the inner heliosphere. Another important parameter for understanding nanodust fragmentation from the larger dust is structure and material strength of the cometary dust and hopefully further analysis of Rosetta results will provide some knowledge on that. The velocities of mutual collisions in the interplanetary dust cloud are between about 20 km/s to few 100 km/s, of same order as in the interstellar medium [cf. 56]. Entry of cometary meteoroids into Earth atmosphere is another example of dust collisions for which we obtain observational data. The impact speeds are several 10 km/s, the material originates from comets and the fragments that remain in the atmosphere have sizes of few nm [see e.g. 3 for further references]. To study the meteor phenomena and the meteoric smoke production is therefore another way forward to understand the formation of nanodust with impacts and collisions.

As far as new observational data on nanodust fluxes are concerned, two upcoming space missions will explore for the first time in detail the inner heliosphere with in-situ measurements. They both carry instruments for field measurements that are expected to also detect signals caused by dust impacts: The Radio and Plasma Waves (RPW) experiment on-board ESA's Solar Orbiter and the Fields Experiment on NASA's Solar Probe Plus mission. Solar Orbiter will make observations in elliptic orbits coming as close as ~60 solar radii (~0.285 au) to the Sun. The aphelia lie outside 0.8 au. And during the 7-year nominal mission time move out of ecliptic as far as 25 degree latitude. Solar Probe Plus moves in elliptic orbits closer to the Sun inward to ~10 solar radii [cf. 57]. These two space missions with different and complementary orbits provide the opportunity to study in detail the inner heliosphere from Earth orbit to the vicinity of the Sun. At present the mass range of dust particles that can be detected with RPW and FIELDS is not determined. This depends, among others, on how the dust impact signals can be distinguished from plasma wave features. The previous dust measurements with antennas cover a broad range of sizes. The STEREO observations cover with different observations modes the mass ranges 10^{-22} to 10^{-20} kg and 10^{-17} to 10^{-15} kg [13] estimated on comparing the flux to other observations and the largest dust mass reported from measurement with antennas in the interplanetary medium is 10^{-14} kg [58].

References

1. Levasseur-Regourd, A.C., Mann, I., Dumont, R., Hanner, M.S. 2001, Optical and Thermal Properties of Interplanetary Dust in: (E. Grün, B.A.S. Gustafson, S. Dermott, H. Fechtig Eds.) Interplanetary Dust, Astronomy and Astrophysics Library, 57- 94 (Springer Springer, Heidelberg).
2. Grün, E., Gustafson, B., Mann, I., et al. 1994, Interstellar Dust in the Heliosphere, Astron. Astrophys. 286, 915.
3. Mann, I., Meyer–Vernet, N., Czechowski, A. 2014, Dust in the Planetary System: Dust Interactions in Space Plasmas of the Solar System, Physics Reports, Vol. 536 1.
4. Ishimoto, H., Mann, I. 1999, Modeling the particle Mass Distribution within 1 AU, Planet. Space Sci. 47, 225.
5. Mann, I., Kimura, H., Biesecker, D.A., et al. 2004, Dust Near the Sun, Space Sci. Rev.110, 269.
6. Mann, I., Murad, E., Czechowski, A. 2007, Nanoparticles in the inner solar System, Planet. Space Sci. 55, 1000.
7. Czechowski, A., Mann, I. 2010, Formation and acceleration of nano dust in the inner heliosphere, Astrophys. J. 714, 89.
8. Meyer-Vernet, N., Maksimovic, M., Czechowski, A. et al. 2009, Dust detection by the wave instrument on Stereo: nanoparticles picked-up by the solar wind? Solar Physics, 256, 463.
9. Mann, I., Koehler, M, Kimura, H., Czechowski, A., Minato, T. 2006, Dust in the solar system and in extra-solar planetary systems, Astron. Astrophys. Rev. 13, 159.
10. Mann, I. 2010, Interstellar dust in the solar system, Ann. Rev. Astron. Astrophys, 48, 173.
11. St. Cyr, O. C., Kaiser, M. L., Meyer-Vernet, N., et al. 2009, STEREO SECCHI and S/WAVES Observations of Spacecraft Debris Caused by Micron-Size Interplanetary Dust Impacts, Sol. Phys., 256, 475.
12. Belheouane, S., Zaslavsky, A., Meyer-Vernet, N., et al. 2012, Detection of Interstellar Dust with STEREO/WAVES at 1 AU, Solar Physics, DOI: 10.1007/s11207-012-9995-7.
13. Zaslavsky, A., Meyer-Vernet, N., Mann, I., et al. 2012, Interplanetary dust detection by radio antennas: mass calibration and fluxes measured by STEREO/WAVES, JGR 117, Issue A5, CiteID A05102.
14. Schippers, P. Meyer-Vernet, N., Lecacheux, A., et al. 2014, Nanodust detection near 1 AU from spectral analysis of Cassini/Radio and Plasma Wave Science data, Geophys. Res. Let. 41, 5382.
15. Malaspina, D. M., Horanyi, M., Zaslavsky, A., et al. 2014, Revisiting STEREO interplanetary and interstellar dust flux and mass estimates, GRL, 41:266.
16. Le Chat, G., Issautier, K., Zaslavsky, A., et al. 2015, Effect of the Interplanetary Medium on Nanodust Observations by the Solar Terrestrial Relations Observatory, Sol. Phys., 290, 933.
17. Meyer-Vernet, N., Mann, I., Le Chat, G. et al. 2015, The physics and detection of nanodust in the solar system, Plasma Phys. Control. Fusion, 57, 014015.
18. Zaslavsky A., 2015, Floating potential perturbations due to micrometeoroid impacts: Theory and application to S/WAVES data, JGR 120, 855.
19. Grün, E., Zook, H.A., Fechtig, H., Giese, R.H. 1985, Collisional balance of the meteoritic complex, Icarus 62, 244-272.
20. Schippers, P. Meyer-Vernet, N., Lecacheux, A., et al. 2015, Nanodust Detection between 1 and 5 AU Using Cassini Wave Measurements, Astrophys. J. 806, A77.

21. Czechowski, A., Mann, I. 2012, Nanodust Dynamics in the Interplanetary Space in: (I. Mann, N. Meyer-Vernet, A. Czechowski Eds.) Nanodust in the Solar System: Discoveries and Interpretations, Astrophysics and Space Science Library 385, 47-75, Springer, New York, 2012.
22. Juhasz, A., Horanyi, M., 2013, Dynamics and distribution of nano-dust particles in the inner solar system, GRL 40, 2500.
23. Wyatt, M. 2009, Dynamics of small bodies in planetary systems, in I. Mann, A. Nakamura, T. Mukai (Eds.), Small Bodies in Planetary Systems, Lecture Notes Physics 758, 37-70 (Springer, Heidelberg).
24. Absil, O. Defrère, D., Coudé du Foresto, V., et al. 2013, Searching for companions down to 2 AU from β Pictoris using the L'-band AGPM coronagraph on VLT/NACO, Astron. Astrophys. 555, A104.
25. Czechowski, A., Mann, I. 2007, Collisional vaporization of dust and production of gas in the beta-Pictoris dust disk, Astrophys. J. 660, 1541.
26. Su, K.Y.L., Rieke, G.H., Malhotra, R. et al. 2013, Asteroid belts in debris disk twins: Vega and Fomalhaut, Astrophys. J. 763, A118.
27. Su, K.Y.L., Rieke, G.H., Defrére, D., et al. 2016, The inner debris disk structure in the Fomalhaut planetary system, Astrophys. J. 818, A45.
28. Lebreton, J., van Lieshout, R., Augereau, J.-C. et al. 2013, An interferometric study of the Fomalhaut inner debris disk, Astron. Astrophys. 555, A146.
29. Draine, B.T., Li, A. 2001, Infrared Emission from Interstellar Dust. I. Stochastic Heating of Small Grains, Astrophys. J. 551, 807.
30. Li, A. 2009, Optical properties of dust, in I. Mann, A. Nakamura, T. Mukai (Eds.), Small Bodies in Planetary Systems, Lecture Notes Physics 758, 167-88 (Springer, Heidelberg).
31. Kobayashi, H., Watanabe, S.-I., 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.
32. Mukai, T., Yamamoto, T. 1979, A Model of the Circumsolar Dust Cloud, Publ. Astronom. Soc. Japan 31, 585.
33. Utterback, N. G., & Kissel, J. 1990, Attogram dust cloud a million kilometers from Comet Halley, AJ, 100, 1315.
34. Utterback, N. G., & Kissel, J. 1995, Interpretation of a Glitch Observed in the Very Small Dust Grain Data at Halley's Comet, Ap&SS, 225, 327.
35. Tuzzolino, A. J., Economou, T. E., Clark, B. C., et al. 2004, Dust Measurements in the Coma of Comet 81P/Wild 2 by the Dust Flux Monitor Instrument, Science, 304, 1776.
36. Konno, I., Huebner, W. F., & Boice, D. C. 1993, A model of dust fragmentation in near-nucleus jet-like features on Comet P/Halley, Icarus, 101, 84.
37. Combi, M., Huang, B., Cochran, A., Fink, U., & Schulz, R. 1994, Time-dependent analysis of 8 days of CN spatial profiles in comet P/Halley, ApJ, 435, 870.
38. Schleicher, D. G., & Osip, D. J. 2002, Long- and Short-Term Photometric Behavior of Comet Hyakutake (1996 B2), Icarus, 159, 210.
39. Snios, B., Lewkow, N., & Kharchenko, V. 2014, Cometary emissions induced by scattering and fluorescence of solar X-rays, A&A, 568, A80.
40. Szego, K., Juhasz, A., & Bebesi, Z. 2014, Possible observation of charged nanodust from comet 67P/Churyumov-Gerasimenko: An analysis for the ROSETTA mission, Planet. Space Sci., 99, 48
41. Gunell. H, Mann, I., Simon Wedlund C., et al.2015, Acceleration of ions and nano dust at a comet in the solar wind, Planet. Space Sci. 119, 13.
42. Kallio, E., Janhunen, P. 2003, Modelling the solar wind interaction with Mercury by a quasi-neutral hybrid model, Ann.Geophys. 21,2133.
43. Gombosi, T.I., Burch, J.L., Horanyi, M 2015, Negatively charged nano-grains at 67P/Churyumov-Gerasimenko Astron. Astrophys. 583, id. A23.
44. Burch, J.L., Gombosi, T.I., Clark, G., Mokashi, P., Goldstein, R. 2016, Observation of charged nanograins at comet 67P/Churyumov-Gerasimenko, GRL 42, 6575, doi:10.1002/2015GL065177.
45. Bentley, A.S., Schmied, R., Mannel, T., et al. 2016, Aggregate dust particles at comet 67P/Churyumov-Gerasimenko, Nature 537, 7618, 73
46. Mannel, T., Bentley, M. S., Schmied, R., et al. 2016, Fractal cometary dust - a window into the early Solar system, MNRS 462, S304.
47. Schmied, R. Mannel, T., Torkar, K., et al. 2016, Morphology of Cometary Dust at the Nanometre Scale Detected with MIDAS, Microsc. Microanal. 22 (Suppl 3) 1776, doi:10.1017/S1431927616009727.

48. Langevin, Y., Hilchenbach, M., Ligier, N. 2016, Typology of dust particles collected by the COSIMA mass spectrometer in the inner coma of 67P/Churyumov Gerasimenko, Icarus 271, 76.
49. Fray, N., Bardyn, A., Cottin, H., et al. 2016, High-molecular-weight organic matter in the particles of comet 67P/Churyumov-Gerasimenko, Nature 538, 72.
50. Della Corte, V. Rotundi, A., Fulle, M., et al. 2016, 67P/C-G inner coma dust properties from 2.2 au inbound to 2.0 au outbound to the Sun, MNRAS 462, S210, doi:10.1093/mnras/stw2529.
51. Lasue, J., Levasseur-Regourd, A. C., Fray, N., Cottin, H. 2007, Inferring the interplanetary dust properties. from remote observations and simulations, Astron. Astrophys 473, 641.
52. Nesvorný, D., Jenniskens, P., Levison, H.F. et al. 2010, Cometary Origin of the Zodiacal Cloud and Carbonaceous Micrometeorites. Implications for Hot Debris Disk, Astrophys. J. 713, 816.
53. Rowan-Robinson, M., May, B. 2013, An improved model for the infrared emission from the zodiacal dust cloud: cometary, asteroidal and interstellar dust, MNRS 429, 2894.
54. Wooden, D.H., Cook, A.M., Colaprete, A., Glenar, D.A., Stubbs, T.J., Shirley, M. 2016, Evidence for a dynamic nanodust cloud enveloping the Moon, Nature Geosci. 9, 665.
55. Vasylyev, V.P., Kalinichenko, A.I., Vasylyev, S.V. 2004, Attogram dust grains in the solar system, Forming mechanism, properties and dynamics, Astron. Astrophys. 415, 781.
56. Jones, A. P., Tielens, A. G. G. M., & Hollenbach, D. J. 1996, Grain Shattering in Shocks: The Interstellar Grain Size Distribution, ApJ, 469, 740.
57. Bale, S.D., K. Goetz K., Harvey, P.R., et al. 2016, The FIELDS Instrument Suite for Solar Probe Plus, Space Sci. Rev. DOI 10.1007/s11214-016-0244-5.
58. Gurnett, D., 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, GRL 24, 312.

Figure captions

Figure 1

Cumulative dust flux as function of mass near 1 AU in the interplanetary medium. The in-situ results are shown are denoted as Meyer-Vernet et al. (2009) from [8], Zaslavsky et al. 2012 from [13] and from [14] (this work) the heavy line shows the interplanetary dust flux model [19] and for masses < 10^{-19} kg its suggested extrapolation based on the new observations (Figure from [14]).

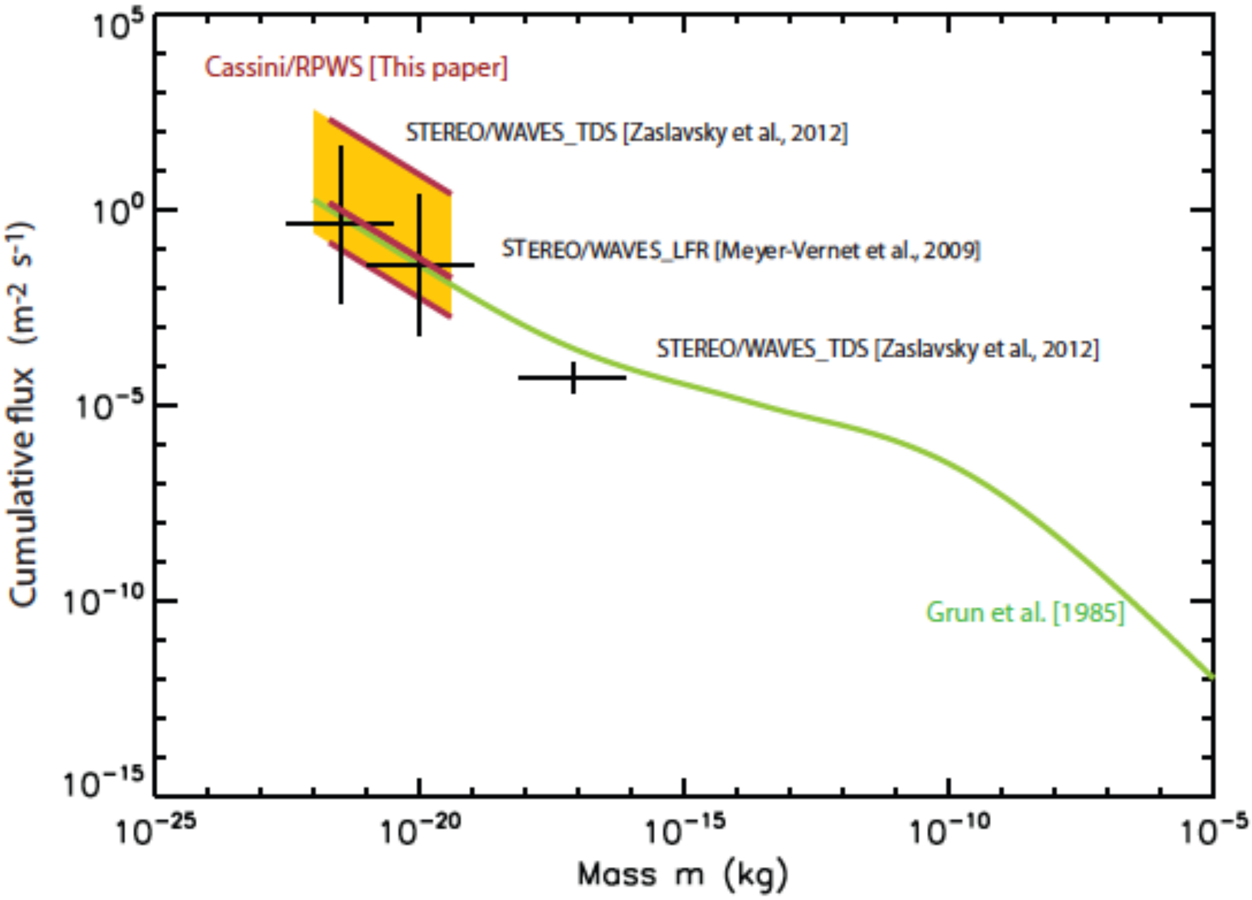
Figure 2

Orbits in the ecliptic of two particles that were released from the same point at 0.12 AU distance from the Sun, the particles are having different values of surface charge to mass corresponding to estimated sizes of 1 and 3 nm respectively (Fig. 2a, from [7], reproduced by permission of AAS). Trapping mechanisms shown in the guiding centre motion along the rotating magnetic field line. The outer boundary of the trapping region is near the point r_1 where the outward-directed centrifugal force associated with the rotation of the magnetic field line exceeds the gravity force. The inner boundary is near r_2 where the outward-directed magnetic mirror force balances gravity (Fig. 2b, adapted from [3]).

Figure 3

Stellar spectrum (upper line) and model of circum-stellar dust emission brightness (lower solid line) explaining hot infrared excess with nanodust within 0.2 AU around VEGA. Hot dust emission peaks ≈ 2 μm and is enhanced around 10 μm because of small particle effects (Figure from [26], reproduced by permission of AAS).

Figure 1



Cassini/RPWS [This paper]
STEREO/WAVES_TDS [Zaslavsky et al., 2012]
STEREO/WAVES_LFR [Meyer-Vernet et al., 2009]
STEREO/WAVES_TDS [Zaslavsky et al., 2012]
Grun et al. [1985]
Cumulative flux (m-2 s-1)
Mass m (kg)
10^5
10^0
10^-5
10^-10
10^-15
10^-25
10^-20
10^-15
10^-10
10^-5

Figure 2

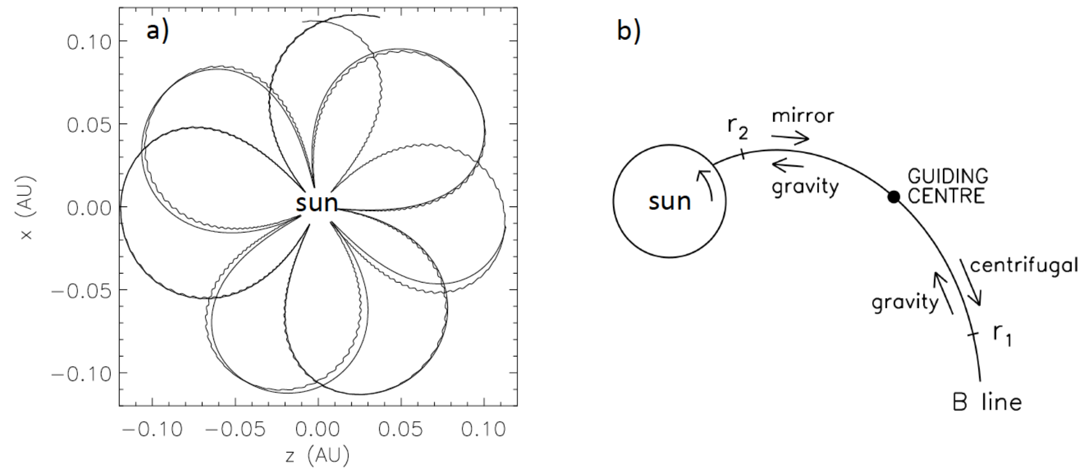
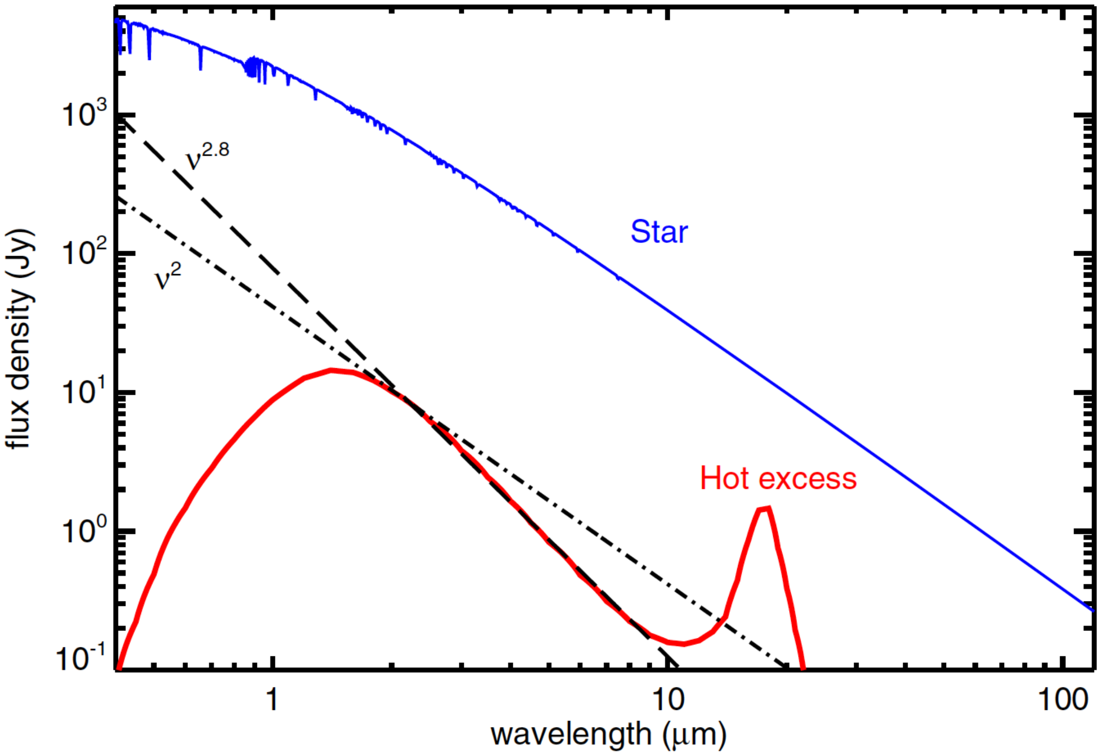

a)
0.10
0.05
0.00
−0.05
−0.10
x (AU)
sun
−0.10
−0.05
0.00
0.05
0.10
z (AU)
b)
sun
r2
mirror
gravity
GUIDING
CENTRE
centrifugal
gravity
r1
B line

Figure 3



10^3
10^2
10^1
10^0
10^{-1}
flux density (Jy)
$\nu^{2.8}$
ν^2
Star
Hot excess
1
10
100
wavelength (μm)