EVIDENCE FOR A SIGNIFICANT KUIPER BELT DUST CONTRIBUTION TO THE ZODIACAL CLOUD

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Interplanetary dust particles (IDPs) are important samples of dust-producing objects in the solar system including many primitive and organic-rich bodies that are not sampled by known meteorites. IDPs spiral in towards the Sun under the influence of Poynting-Robertson (P-R) drag forces and are exposed to solar energetic particles (SEPs) that leave tracks of ionization damage in anhydrous silicate grains. We determined the exposure ages of track-rich IDPs using a new calibration of the SEP track production rate and show that track-rich IDPs have long exposure ages (>1 My) that preclude an origin from main-belt asteroids (MBAs) and Jupiter-family comets (JFCs). We propose that track-rich IDPs represent samples of dust produced by collisions among Edgeworth-Kuiper Belt objects (EKBOs) and that appreciable amounts of EKBO dust are contributing to the Zodiacal cloud. Many track-rich IDPs also contain abundant secondary minerals that provide direct evidence for past aqueous activity on some EKBOs.

IDPs fall within a fortuitous size range – they are sufficiently large to escape ejection from the solar system by radiation pressure yet small enough that their size and optical properties result in orbits that rapidly decay under the influence of P-R drag. Their size, density, and entry velocities allow them to survive entry through Earth's atmosphere and to be collected in the stratosphere. IDPs are a more representative sampling of dust-producing objects in the solar system than larger objects like meteorites that are commonly sourced to a few resonant gaps in the main asteroid belt. The properties and origins of IDPs carry importance far out of proportion to their size because they contain the highest presolar grain abundances[1], the highest carbon contents[2], and the highest abundance of preserved molecular cloud materials[3] compared to meteorites.

During their orbital evolution, IDPs are exposed to an array of energetic particles. For IDPs, the presence of SEP tracks in their constituent mineral grains has long been accepted as proof of their extraterrestrial origin[4], and the observed track densities provide critical constraints on the space exposure age of the particles. The number of IDPs with well-constrained track density measurements is small however, owing to the difficulty in the measurements and the lack of appropriately sized crystals in which to image them. Solar energetic particle tracks in IDPs have only been observed and measured using transmission electron microscope (TEM) imaging techniques, but to use measured track densities to estimate space exposure times, a track production rate must be known. Early work on tracks in IDPs[5,6] used production rate calibrations that were based on chemical etching techniques[7,8] determined from rocks exposed at the lunar surface. Using these calibrations, IDP exposure ages of ~10^4 years were inferred from the observed track densities and these ages appeared consistent with P-R drag times from main-belt asteroids (MBAs) or Jupiter-family comets (JFCs). Recently however, the first track production rate calibration for TEM measurements became available[9] and is 1-2 orders of magnitude lower than the rates determined via chemical etching. The difference between the two calibrations results mainly from the different volume of material probed by the two techniques. The TEM calibration measurements are made on planar samples typically <100 nm thick whereas the chemical etching technique probes a larger volume up to 15 μm thick (the depth of etching), resulting in much higher track counts per unit area compared to the TEM results[9]. Using the track production rate from chemical etching to interpret TEM track measurements significantly underestimates derived space exposure ages. We used the track production rate calibration for TEM measurements[9] to estimate IDP space exposure ages of IDPs and show that the typical track densities observed in IDPs of $>10^{10}$ cm^{-2} (Fig. 1) require space exposures >~1 My, orders of magnitude longer than P-R drag times for dust from MBAs and JFCs.

Results and Discussion

In Table 1 we present our TEM observations to date from 29 IDPs, 16 from the anhydrous group and 13 from the hydrated group showing track densities ranging from ~2×10^{10} up to $5 \times 10^{11}/cm^2$, a range in track densities that is consistent with previous measurements. Dynamical dust models suggest most of the zodiacal dust inside of 5 AU is produced by JFCs and MBAs, with lesser contributions from Edgeworth-Kuiper belt objects (EKBOs) and Oort Cloud comets (OCCs)[10,11]. The latter two sources, however, dominate beyond ~10 AU[12]. For pure P-R drag forces, the ~10-20 μm dust particles released by JFCs and MBAs reach 1 AU in <60,000 y, while dust produced by collisions of EKBOs are estimated to take ~10^7 y[12-15]. Sandford[16] used a numerical approach to calculate the expected track densities in 10 μm IDPs from JFCs and MBAs using a track production rate at 1 AU of $6.5 \times 10^5/cm^2/y$ (2π) (from chemical etching[7]), and a r^{-2} falloff in the SEP flux with heliocentric distance, which gave track densities up to $1 \times 10^{10}/cm^2$. We used the same numerical approach of Sandford[16] to calculate the expected track density from these objects, except that we used the track production rate at 1 AU that is calibrated for TEM measurements[9] of 4.4 (+/-0.4) $\times 10^4$ $/cm^2/y$ and a $r^{-1.7}$ falloff[17] in SEP flux. From these calculations, we derive track densities for IDPs released by JFCs and MBAs ~$10^9/cm^2$, one to two orders-of-magnitude less than the typical observed track densities in IDPs. Even the longest-lived JFC particles in the Zodiacal cloud (~100 μm)[8], those whose P-R drag lifetimes match their collisional disruption lifetimes, cannot accumulate track densities $>10^{10}$ cm^2.

IDPs from MBAs may also be exposed to SEPs in regoliths before they are released to space and subjected to P-R drag. Compared to the lunar surface, the low gravity of asteroidal bodies combined with the high flux of non-catastrophic collisions[18] or tidal shaking from planetary encounters[19] results in short surface exposure times for asteroid regolith grains. The only direct data in this regard comes from asteroid Itokawa[20-22], where SEP track densities in returned mineral grains indicate average surface residence times of ~50,000 y. We calculate a track density of ~7x10^8/cm^2 for an IDP with a regolith residence time at the surface of 10^5 y at 3 AU using a $r^{-1.7}$ model for the heliocentric decay of the SEP flux[17], a 2π irradiation, and the new track production rate[9]. Even by combining the track density accumulated in a particle residing in an MBA regolith with those during its transit from 3 to 1 AU, the resulting track density is still lower by over 1-2 orders-of-magnitude than that observed in our IDPs (Table 1). If the track-rich IDPs are from MBAs, then their track densities imply extremely long (and probably unrealistic) surface residence times (up to 60 My). The other potential sources of track-rich IDPs include OCCs and EKBOs. Particles from OCCs arrive at 1 AU with high entry velocities and undergo strong heating effects during atmospheric entry (e.g., mineral alteration, track annealing), leaving EKBOs as the likely source bodies of track-rich IDPs.

The Edgeworth-Kuiper Belt is the largest source of dust in the solar system with dust production rates nearly two orders-of-magnitude higher than JFCs[23]. Modeling by Poppe et al.[23] gives total dust production rates for EKB, OCC, and JFC grains of 3.5×10^7 g s^{-1}, 3×10^5 g s^{-1}, and 5×10^5 g s^{-1}, respectively. Modeled dust production rates show the "stirred-classical" subpopulation of EKBOs are the most numerous and produce ~60% of EKB dust[9], mostly from bodies with eccentricities < 0.25 and inclinations <10°. The modeled dust production rate in the EKB is almost two orders-of-magnitude greater than that from JFCs[23], thus, EKB particles could contribute significantly to the Zodiacal Cloud. A major question is how much EKB dust survives the journey to the inner solar system?

To reach the inner solar system EKB dust must transit the region of the giant planets, where gravitational interactions can trap dust in mean-motion resonances (MMRs) or even eject it from the solar system. However, most of the 10 μm IDPs collected from the Earth's stratosphere are aggregates, many of them quite porous. Even the more compact hydrated IDPs are aggregates containing anhydrous silicates in which we measured solar energetic particle tracks. When the particles escape these resonances, they almost always pass Uranus and Neptune, and any trapping by Saturn or Jupiter is much shorter than at Uranus and Neptune. Modeling by Liou et al.[24] that included solar radiation pressure and drag, solar wind drag, and for the giant planets, gravity, indicates that much of the dust produced by EKBOs is ejected from the solar system by the giant planets, but ~20% of the ~9 μm dust survives to 1 AU. The modeling also shows that most of these particles are trapped in MMRs exterior to Neptune for periods of millions of years[24].

EKB dust also must survive collisional fragmentation by either interstellar grains transiting the solar system or other Zodiacal Cloud particles during their journey to 1 AU. Liou et al.[24] used the interstellar dust flux measured by Ulysses at Jupiter[25], 8 x 10^{-5}/m^2/s to calculate the average collisional lifetime of the particles they modeled. They found that collisions with interstellar grains did not have a significant effect on the orbital evolution of the 1, 2, or 4 μm diameter grains, but that most of the 9 μm diameter grains were likely destroyed before they reached the Sun. However, modeling the grains as compact, homogeneous spherical silicates having a density of 2.9 g/cm^3 likely overestimates the transit times of these grains. The actual IDPs collected from the stratosphere are generally irregularly shaped, low albedo, carbon-rich, aggregates dominated by silicates and sulfides. Flynn and Sutton[26] combined their bulk density measurements with those of two other groups and found a mean density of 0.6 g/cm^3 for the porous fluffy aggregates and 1.8 g/cm^3 for the platy hydrous aggregates. Mukai et al.[27] calculated the β values for fluffy porous aggregates using Discrete Dipole Approximation. They found that for silicate aggregates the decrease in β with increasing size was less steep than from Mie theory and for graphite aggregates the variation of β with size was quite small, especially for high porosity. If there is minimal variation of the optical properties of the dust with size, as seems likely for the dark, carbon-rich IDPs, then the P-R orbital evolution timescale is proportional to the product of particle diameter and density. In that case a 4 μm 2.9 g/cm^3 particle would experience similar P-R orbital evolution to a 12 μm 1 g/cm^3 particle and a 9 μm 2.9 g/cm^3 particle would have an orbital evolution timescale comparable to a 26 μm 1 g/cm^3 particle. Thus 10 μm diameter and possibly even 20 μm porous IDPs likely escape destruction as collisional probabilities decrease with decreasing size and in particular, particles <100 μm grains are unlikely to suffer collisions once inside Jupiter's orbit[10].

High atmospheric entry velocities result in strong heating of IDP-sized particles which alters the mineralogy of the particles and can erase tracks by thermal annealing[4]. The track-rich IDPs discussed here show minimal heating effects in their mineralogy and so we assume in our modeling that they entered the atmosphere with low encounter velocities from circularized orbits.

We calculate the expected track density for spherical EKB IDPs whose orbits evolve under pure P-R drag using the new track production rate[9], a $r^{-1.7}$ falloff model for the heliocentric decay of the SEP flux[17], and 4π irradiation. We performed the calculations for 4 model particles (Table 2). We modeled individual anhydrous chondritic-porous IDPs as 10 μm diameter particles with a bulk density of 1 g/cm^3 and individual hydrated chondritic-smooth IDPs as 20 μm diameter particles with a bulk density of 2 g/cm^3 (Models 1 and 2 in Table 2, respectively). The modeled particle densities are based on previous IDP measurements[26]. Most of the anhydrous IDPs (13 of 16, Table 1) and a few of the hydrated IDPs (4 of 13) are fragments of larger cluster particles whose original diameters are estimated to be >50 μm, and so we also calculated track densities for a model for anhydrous cluster particles as 50 μm diameter particles with a bulk density of 1 g/cm^3 and for hydrated cluster particles as 50 μm diameter particles with a bulk density of 2 g/cm^3 (Models 3 and 4 in Table 2, respectively). Our calculated EKB particle track densities fall on the low side of the range of track densities displayed by the track-rich IDPs implying that an additional source of tracks needs to be considered or that resonance trapping is increasing the exposure time of the IDPs to the SEP flux. Measured track densities for anhydrous and hydrated IDPs are tightly clustered around ~6×10^{10} cm^{-2} (Figure 2), this is a puzzling result until one considers that a 20 μm diameter 2 g/cm^3 hydrated particle (Model 2) has nearly the same P-R drag time as a 50 μm 1 g/cm^3 anhydrous cluster particle (Model 3) resulting in similar accumulated track densities (Table 2). Alternatively, the anhydrous IDPs may be derived from objects at greater heliocentric distance with corresponding longer P-R drag times.

Modeling indicates that most EKB particles are trapped in exterior MMRs with Neptune, typically for 10 to 50 million years[24], so we modeled the SEP track accumulation during 10 and 50 My residences in these resonances (between ~30 and 38 AU). A particle trapped at 35 AU for

10^7 years would accumulate ~2.1 x 10^9 tracks cm^{-2}, which would increase the total track density in a 10 μm IDP originating at 50 AU by about 50%, but would not significantly alter the track densities in the larger particles in Table 2, since their P-R orbital evolution times are much longer. A 50 My trapping in an MMR exterior to Neptune, consistent with some of the longer trapping times reported for 9 μm density 2.9 g/cm^3 grains[24], would increase the track density to 10.5 x 10^9 tracks cm^{-2}, which is sufficient to match the track densities in many of the track-rich IDPs when added to the tracks accumulated during their orbital evolution to 1 AU. One 9 μm particle remained trapped for 150 x 10^6 y, but that particle was ultimately ejected from the solar system[24].

EKB IDPs spend the majority of their time in the outer solar system, where the track production rate from SEP ions is much lower than at 1 AU, but the flux of galactic cosmic rays is much higher[28]. This potentially would increase the expected track densities for EKB IDPs over the values shown in Table 2, but a calibration for TEM-measured GCR tracks is lacking and precludes a reliable estimate of the GCR contribution to the track density in EKB-derived IDPs. The typical observed GCR track production rates determined from chemical etching studies of lunar materials[29] are on the order of ~10^5-10^6 tracks/My. It is unclear however, if high energy GCRs would produce tracks in free-floating 10-20 μm particles given that GCRs only produce tracks near the end of their trajectory after penetrating to ~meter depths. The track-rich IDPs may have accumulated GCR tracks while part of a larger body and these would be in addition to the SEP tracks added after its release from an parent body.

We estimate that track-rich IDPs comprise ~25% of all the IDPs we have analyzed from NASA's stratospheric dust collections although their precise proportion is poorly constrained because systematic studies are lacking, and numerous variables can affect this proportion based on survivability and characterization limitations. A major implication of this result is that EKB objects are contributing a significant amount of the dust that comprises the Zodiacal cloud. Dust from EKB objects arrive at 1 AU with highly circularized, low-eccentricity orbits with low velocities that enhance their survival during atmospheric entry[24]. The orbits of these EKB particles are indistinguishable from the low entry speed tail of the JFC dynamical distribution obtained from modeling studies by Nesvorny[10]. The EKB particles are likely similar in composition and mineralogy to JFC particles given that most JFCs are believed to originate in the EKB. However, as shown here, track densities which are a measure the duration of exposure to SEPs, provide a rigorous criterion to distinguish particles that have evolved directly from the EKB under P-R drag from those that were transported to the inner solar system in JFCs and released much more recently into the Zodiacal Cloud.

The IDPs that lack observable tracks could have multiple origins. For the IDPs that have not been strongly heated during atmospheric entry and contain crystalline grains capable of recording tracks, the lack of tracks likely indicates short exposure ages and an origin from either a JFC or MBA source. For strongly heated IDPs, the lack of tracks makes source attribution equivocal.

The mineralogy of track-rich IDPs includes examples from both the anhydrous and hydrated classes of IDPs. The anhydrous class are typically high porosity objects consisting of an unequilibrated assemblage of high temperature mineral grains (olivine and pyroxene), FeNi sulfides, and amorphous silicates bound together by an abundant carbonaceous/organic-rich matrix. The track-rich hydrated IDPs are low porosity objects dominated by minerals such as clay minerals, Mg-Fe carbonates, and magnetite that formed via aqueous processes. The hydrated IDPs are also rich in organic carbon. The extent of aqueous alteration and the mineralogy of hydrated IDPs are most similar to the CI carbonaceous chondrites, although their isotopic compositions and carbon abundances are distinctly different[30]. The presence of hydrated minerals on two Kuiper belt objects was inferred based on reflectance spectra showing a weak 0.7 μm absorption attributed to an Fe^{2+}-Fe^{3+} charge transfer transition from oxidized iron in phyllosilicates[31].

There are multiple potential sources of liquid water in EKBOs. The larger objects, if they accreted early, may have contained sufficient radiogenic elements to mobilize (melt) interior volatiles[32], although the Al-Mg isotopic systematics from comet 81P/Wild samples[33-35] suggest late accretion of that Kuiper belt object after the decay of ^{26}Al. Aqueous fluids could have been produced during low velocity collisional processes among EKBOs that resulted in transient heating sufficient to melt water ice. Track-rich IDPs with mixed anhydrous/hydrated mineralogy are known and show the preferential alteration of amorphous silicates to clay minerals[36]. Laboratory hydration experiments on anhydrous IDPs have shown that the fine-grained amorphous silicates readily and rapidly hydrate in the presence of liquid water to produce clay minerals[36]. Previous work showed that the hydrated and anhydrous IDPs show similar elevated carbon contents relative to known meteorites and that the hydrated IDPs may simply represent anhydrous material that interacted with liquid water[37].

Methods

The IDPs in Table 1 reflect a sampling of C-type IDPs (particles with an approximate chondritic elemental spectrum) that were randomly selected from cosmic dust catalogues prepared and published by the NASA Johnson Space Center Curatorial facility. Some of the IDPs are fragments of cluster particles, larger (~<50 μm) particles that broke into multiple fragments on the collector surfaces (indicated by an *). The IDPs are embedded in low viscosity epoxy or elemental sulfur and thin sections ~50-70 nm thick are obtained using ultramicrotomy. We used a combination of brightfield and darkfield imaging in a scanning and transmission electron microscope (STEM) to image tracks in microtome thin sections of IDPs. For the IDPs in Table 1, we imaged tracks in multiple grains, and where possible, in multiple phases within the same particle. It has been demonstrated that anorthite and olivine record similar track densities for similar exposures[9], and here, we assume pyroxene behaves similarly as noted by Fraundorf[4]. We note that in three of the IDPs in Table 1, tracks were measured in multiple minerals including pyroxene, olivine and anorthite and all three display the same track density in the different minerals. One limitation to this data is that the mineral grains in IDPs are typically sub-μm in size, which limits the lowest track densities than can be reliably measured in the STEM (e.g., 1 track in 1 μm^2 equates to a density of 10^8 tracks/cm^2, 1 track in 100 nm^2 is $1x10^{10}$ tracks/cm^2). The chattering and fracturing of mineral grains during sample preparation using microtomy also complicates these measurements. Finally, for the hydrated IDPs, unambiguous identification of tracks in fine-grained phyllosilicates is generally not possible given their grain size and complex microstructures and intergrowths. In addition, surviving anhydrous silicates that record tracks are rare in hydrated IDPs. For these reasons, we typically counted the number of tracks present in 100 nm^2 regions of uniform contrast in the TEM images. In the Supplemental data section, we present images and track counts using this procedure for the IDPs in Table 1. For IDPs L2009O1 and L2011R11 we cite previous images and reported track density data[34, 37].

We calculate track densities for IDPs whose orbits evolve by pure P-R drag forces. We use the formulation from Equation 7 presented by Wyatt and Whipple[38]:

$$t = 7.0\text{x } 10^6\, s\rho a^2,$$

Where t is the P-R transit time in years, s is the particle radius (cm), ρ is the particle density (g/cm^3), and a is the heliocentric distance (in astronomical units). For our calculations, we assumed a range of particle diameters and bulk densities for particles starting with circularized orbits. We use a track production rate of $8.8\text{x}10^4$ tracks/y (for a 4π exposure) and a $1/r^{1.7}$ model[17] for the fall-off of the track production with heliocentric distance to calculate the number of tracks accumulated during the particle transit to 1 AU. We calculated track densities for 4 particle models (Table 2).

We also consider whether near-Earth asteroids (NEAs) such as Bennu or Ryugu could be potential source bodies for the track-rich hydrated IDPs in our study. Analysis of the returned samples from Ryugu are in progress, and samples from Bennu will be returned to Earth in September 2023. The analysis of these samples will directly determine the surface exposure histories of these bodies, but until those results become available, we consider several other lines of evidence. As noted above, samples from the NEA Itokawa have track densities[21,22] that are orders of magnitude lower than those in the IDPs corresponding to direct exposures to SEP particles in the Itokawa regolith for $<10^4$-10^5 years. This low surface exposure age is consistent with resurfacing rates for NEAs such as Itokawa, Bennu, and Ryugu inferred from crater retention ages in their nearly cohesionless regoliths[39]. These observations suggest that typical surface exposure ages for NEAs are too short to accumulate the high track densities observed in the hydrated IDPs. The chemical compositions of Ryugu samples are also distinct from the hydrated IDPs in this study. Recent results from analyses of Ryugu samples show carbon abundances that are comparable to CI abundance[40], whereas the hydrated IDPs have carbon abundances that are typically ~4XCI[35], similar to the anhydrous IDPs. The chemical similarity between anhydrous and hydrated IDPs suggests a genetic relationship between the groups[35]. This latter point is further supported by studies of so-called “hybrid IDPs” where the mineralogy shows anhydrous materials directly altering to hydrated minerals typical of hydrated IDPs. Finally, NEAs are not a significant source of dust to the Zodiacal cloud and so the collection probability for dust from these objects is low based on the absence of dust trails associated with any NEAs in the spacecraft infrared data[41].

Data Availability

The data are provided in the article and the supplemental file. Correspondence and requests for materials should be addressed to Lindsay.P.Keller@nasa.gov.

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Author Contributions

LPK measured track densities and wrote parts of the manuscript, GJF preformed the track density calculations and wrote parts of the manuscript.

Competing Interests

The authors declare no competing interests.

Tab. 1. Solar energetic particle track-rich IDPs in this study. Data for measured track densities, host mineral for tracks, and the whether the IDP is anhydrous ("anhyd") or hydrated ("hyd"). The image data are collected in the supplemental data file.

IDP	tracks/cm^2 (x 10^{10})	Host mineral	IDP type	Cluster fragment
L2005*A3	8	olivine	anhyd	y
L2036*C11	6	anorthite	anhyd	y
L2036*B61	10	pyroxene	anhyd	y
L2036*C46	7	anorthite	anhyd	y
L2036*C41	8	pyroxene	anhyd	y
L2011B10	3	pyroxene	anhyd	y
L2005F31	5	pyroxene	anhyd	y
L2005Q4	5	pyroxene	anhyd	
L2009H11	8	pyroxene	anhyd	
L2036AW1	8	olivine	anhyd	y
L2036AA*4	20	olivine	anhyd	y
L2009O1[34]	15	pyroxene	anhyd	y
L2009*E2	5	pyrox	anhyd	y
L2011R11[39]	4	oliv, pyrox	anhyd	
L2009D11	15	pyrox, anorth	anhyd	y
L2036AY1	5	oliv, pyrox	anhyd	y
L2011*B5	6	pyroxene	hyd	y
L2006O15	7	pyroxene	hyd	

L2005Q1	50	olivine	hyd	
L2079C35	6	pyroxene	hyd	
U2153M1	5	olivine	hyd	y
U2153L1	5	pyroxene	hyd	y
L2083E46	6	quartz	hyd	
L2083E25	8	pyroxene	hyd	
L2098B1	15	pyroxene	hyd	
L2083D58	5	pyroxene	hyd	
L2083E47	7	quartz	hyd	
L2005P9	3	olivine	hyd	
L2009O4	10	pyroxene	hyd	y

Tab. 2. Modeled track densities (tracks/cm^2 x10^9). Calculated track densities for 4 different models of spherical particles with a range of diameters and bulk densities, starting in near-circular orbits, and evolving under P-R drag to 1 AU. For each calculation, we use a $1/r^{1.7}$ model[15] for the fall off in track production with heliocentric distance, and a track production rate[5] at 1 AU of 8.8x10^4 tracks/cm^2 (4π).

Distance (AU)	1 10 μm, ρ= 1	2 20 μm, ρ= 2	3 50 μm, ρ= 1	4 50 μm, ρ= 2
50	4.6	18.3	22.9	45.7
40	4.1	16.6	20.7	41.4
30	3.6	14.5	18.2	36.3
20	3.0	11.9	14.9	29.8
15	2.6	10.2	12.8	25.6
10	2.0	8.2	10.2	20.4
5	1.3	5.1	6.4	12.8
3	0.8	3.2	3.9	7.9
2	0.5	1.9	2.3	4.6

Fig. 1. Solar Energetic Particle (SEP) Tracks in a pyroxene grain. (left) A darkfield transmission electron microscope image of a pyroxene grain in hydrated IDP L2006Q4 showing ~6x10^{10} tracks/cm^2. The green lines in the image on the right highlight individual SEP tracks.

Fig. 2. Distribution of Track Densities. Measured track densities in anhydrous (blue) and hydrated (red) IDPs showing a strong clustering of the observations around ~6x10^{10} tracks cm^{-2}.

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