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Cosmic dust in space and on Earth

Cosmic dust provides insights into solar system evolution, but more effort is needed to connect astronomical observations with studies of samples collected at Earth and samples returned by space missions. **Penny Wozniakiewicz** reports on an RAS Specialist Discussion Meeting from December 2015.

Cosmic dust, consisting of particles less than a few millimetres in diameter, is a universal phenomenon and an important component in the history of all planetary systems. Dust and gas make up the molecular clouds in which planetary systems originate, collapsing to form stars and their protoplanetary discs. Assuming a similar evolutionary path to that of our own solar system, accretion within these discs can ultimately produce planets and minor bodies such as asteroids and comets. Eventually, stellar winds begin to clear residual primordial dust and gas, but dust remains between the planets, continually replenished by impact events between solid bodies, particularly the airless, low-mass (and hence low escape velocity) asteroids and comets. Comets sent into the inner solar system by gravitational perturbations can also generate large quantities of dust, as solar heating removes the icy materials that bind together their rocky components and they begin to disintegrate. Finally, as stars enter the later stages of their lifetimes, large volumes of dust and gas can be generated and ejected out into space, perhaps eventually becoming incorporated into the molecular clouds that will produce the next generation of stars and planetary systems.

The analysis of cosmic dust can therefore provide snapshots of the contents, conditions and processes operating in solar systems at various stages of their evolution. In our own solar system, interplanetary dust is primarily derived from comets and asteroids, and is responsible for a phenomenon observed from Earth called the zodiacal light – a faint, diffuse white glow that, in favourable observing conditions, can be seen to extend along the ecliptic (figure 1).

Orbital debris

A further source of dust in space – potentially unique to our own solar system – is the debris that we generate as a consequence of populating low Earth orbit with satellites and exploring our solar system with spacecraft. This debris typically consists of spacecraft materials degraded over time by exposure to the harsh environment of space (e.g. paint flakes, pieces of insulation) and exhaust particles and erosion debris from solid rocket motors. Internal explosions caused by inadequately vented residual propellant in spent bodies can also produce multiple fragments.

Another major contributor to orbital debris has been the break-up of Earth-orbiting spacecraft as a result of impact. For example, in 2009 a collision between Iridium 33, an operational US-built communications satellite, and Kosmos-2251, a deactivated Russian military satellite, destroyed both satellites and created more than a thousand pieces of debris >10 cm across, many of which still pose a threat to spacecraft today (Orbital Debris Quarterly News July 2011). Astonishingly, one of the largest populations of orbital debris was produced by an intentional impact: in 2007, China conducted an anti-satellite missile test, purposefully destroying one of its Fengyun weather satellites and creating more than 2000 pieces of debris >10 cm (Kelso 2007). In both cases, as well as the observed cm-scale fragments, many more smaller fragments were produced. As we continue to explore and populate our solar system with spacecraft, this dust, as well naturally occurring cosmic dust, is becoming an increasing concern, prompting efforts to monitor levels and investigate and mitigate the hazards they pose.

The December 2015 RAS Specialist Discussion Meeting was entitled Cosmic Dust in Space and on Earth: Interplanetary, Interstellar and Artificial. It aimed to bring together researchers involved in the study of both natural and anthropogenic cosmic dust, including those studying data from observatories and space missions, analysing mission-returned samples and cosmic dust collected on Earth, as well as those performing relevant modelling and experiments.

Cosmic dust analysis

Characteristics such as the composition, crystallographic structure and morphology of cosmic dust particles can provide a record of the environments in which they formed – e.g. temperature, pressure, materials available, and heating and cooling rate – and/or any subsequent processing they have experienced since accretion on their parent bodies, such as exposure to water or heat. This arises because, for example, a condensing gas or cooling melt will form different minerals or different mineral structures according to the surrounding environmental conditions. Therefore cosmic dust can provide details of the conditions and processes operating in different environments, around other stars and planetary systems and within molecular clouds.

Cosmic dust in our own solar system can be studied in various ways (table 1). Those particles arriving at, or close to, the Earth can be collected passively and readily studied in the laboratory. Samples collected actively by spacecraft travelling through interplanetary space or as they rendezvous with other solar system bodies, can be studied either in situ if the spacecraft has the necessary instrumentation, or in laboratories back on Earth if it is a sample-return mission. Independently, Earth and space-based telescopes can perform remote observations of dust, both within and beyond our solar system, collecting images and spectra at various wavelengths. Finally, dust that predates our solar system can be found and identified as presolar grains with exotic isotopic signatures among samples of cosmic dust and meteorites. These surviving grains provide a valuable additional source of information on extrasolar environments. Indeed, “fresh” extrasolar dust continues to penetrate into the solar system and has been detected by several space missions, with some candidates even being captured in space and returned to Earth for analysis.

Micrometeorites

Despite their small size, it is estimated that ~40 000 tonnes of extraterrestrial material arrives at the Earth every year in the form of dust (Love & Brownlee 1993), greatly outweighing the ~50 tonnes that arrives as larger meteorites (Zolensky et al. 2006). Approximately 90% of this dusty material is thought to be vaporized as it enters the atmosphere, yet this still leaves a large mass of material reaching the surface and being potentially available for study (Taylor et al. 1998). Those particles that make it to the Earth’s surface are called micrometeorites. Compared to larger meteorites, the study of micrometeorites is still in its infancy, primarily due to the difficulties we face when trying to collect them.

When directly compared, micrometeorites may be distinguished from natural and man-made terrestrial dust particles by the presence of a magnetite shell (figure 2a), that results from atmospheric entry heating, Ni-bearing iron metal or chondritic bulk compositions as well as characteristic isotope and noble gas abundances (Genge et al. 2008). Micrometeorites may also exhibit further evidence of heating from atmospheric entry such as spherical particle morphologies, in which case they are often referred to as cosmic spherules (figure 2b). In addition, the olivines are commonly Fe-poor and contain Ca and Cr which are rare compositions among terrestrial rocks (Brearley & Jones 1998). However, in most locations on Earth, the background terrestrial dust vastly outnumbers the incoming micrometeorites, completely obscuring them and making any grain-by-grain search and subsequent analysis a tremendous feat. As a consequence, the successful collection of micrometeorites requires either the application of some separation technique or an approach that limits the amount of background terrestrial dust.

Using magnets, metal-bearing micrometeorites have been successfully separated from deep sea sediments (e.g. Fredriksson 1956, Pettersson & Fredriksson 1958, Brownlee et al. 1979) and dissolved prehistoric limestones (e.g. Dredge et al. 2010) and evaporites (e.g. Davidson et al. 2007). Recently they have even been separated from dust collected in urban environments (Genge et al. 2016). However, not all micrometeorites will be magnetic; hence these samples do not represent the entire incident population. The collections are also likely to be weathered and biased towards harder wearing types by the prolonged exposure to terrestrial processing that they undergo.

More complete collections have been obtained from ices and snows from polar regions – locations where the terrestrial dust flux is so low that micrometeorites represent a major dust component and additional separation techniques are not required (e.g. Taylor et al. 1998, Maurette et al. 1991, Engrand & Maurette 1998, Duprat et al. 2007). These samples have permitted the construction of a classification scheme (Genge et al. 2008) and allowed estimates to be made of the flux of material surviving atmospheric entry and arriving at the Earth's surface (Taylor et al. 1998), highlighting the potential role of cosmic dust as a source of volatile materials to the Earth and other planets. The effects of atmospheric entry heating can complicate the interpretation of characteristics inherent to the particle and parent body processes it has experienced, and of incoming abundances of different micrometeorite types: **Martin Suttle** (Imperial College London) described his work using the Raman signatures of carbonaceous matter in micrometeorites to resolve primary parent body signals from secondary entry heating overprints.

Compositional (major, minor and trace element abundances), isotopic and textural studies of micrometeorites have also shown that while a large number of micrometeorites share affinities with meteorite groups (e.g. Kurat et al. 1994, Genge et al. 1997, Genge 2008), some exhibit distinct characteristics attributed to bodies not represented in current meteorite collections, e.g. ultracarbonaceous micrometeorites (Nakamura et al. 2005, Duprat et al. 2010). This idea was reiterated by **Matthias Van Ginneken** (Vrije Universiteit Brussel), who described how high-precision oxygen isotope analyses of large micrometeorites were producing numerous signatures indicative of parent bodies unsampled by meteorite collections (Suavet et al. 2010, Van Ginneken et al. 2015a). The reason is that, compared to micrometeorites, meteorites are a heavily biased sample set: they are only produced from those bodies which have suffered a large scale impact event, and only arrive at the Earth if their orbits have been modified by gravitational interactions with other bodies onto Earth-crossing orbits. In comparison, micrometeorites are produced by any dust-producing bodies and, once liberated from their parent body, they begin to spiral inwards or outwards (depending on their size), gradually migrating across the solar system.

Micrometeorites therefore have the potential to complement and expand upon existing meteorite collections and provide a more complete picture of the content of, and processes occurring in, the solar system. Because of this potential, further efforts to develop more effective methods of collection continue to be made. **Matt Genge** (Imperial College London) described a recent Antarctic collection from the Transantarctic Mountains, recovered from moraine at the Larkman Nunatak. Although moraine locations have an abundance of local terrestrial sediment, the material has the significant advantage of being comparatively easy to collect and prepare for searching, with no need to melt and filter huge quantities of ice/snow (Suttle et al. 2015).

However, a complication that this and the other Antarctic collections extracted from terrestrial snows/ices suffer from is that they are between tens and thousands of years old. Consequently, they often exhibit terrestrial alteration that complicates their interpretation (Terada et al. 2001, Suzuki et al. 2010, Van Ginneken et al. 2015b). They are also biased towards less-fragile sample types. In addition, knowledge of individual particle arrival times are uncertain, being at best defined ±years or ±decades, so that links to celestial events such as meteor showers cannot be made. Furthermore, these collections have typically focused on particles >50 μm in diameter: the flux of particles varies according to their size, with far greater numbers of the smaller sizes. Consequently, for those studies focusing on larger specimens, long collection times are required to obtain reliable statistics. **Penny Wozniakiewicz** (University of Kent) described her group's attempts to collect and study all particles arriving at the Earth's surface down to 5 μm in diameter while avoiding the issues that plague long-duration Antarctic collections. They used a new micrometeorite collection technique based on high-volume air samplers fitted with filters – changed weekly – that collect particles directly from the atmosphere at ground level. Their first attempt has been conducted on Kwajalein atoll in the mid-Pacific (Wozniakiewicz et al. 2014), but the collections have been found to contain a larger proportion of terrestrial contamination than hoped. Nevertheless, with their characteristic spherical morphology, a range of cosmic spherule candidates have been identified showing that the method is viable (figure 2c). She also introduced the next generation of this collection, performed between February and July 2015 in collaboration with the British Antarctic Survey in the Clean Air Sector Laboratory (CASLab) at Halley VI Research Station, Antarctica. CASLab is designed specifically to enable the sampling of "clean atmosphere" and is located 1 km downwind from Halley to ensure minimal contamination by local anthropogenic activities. Consequently, the group anticipates being able to locate and analyse all types of micrometeorite collected on the new filters. The samples were returned to the UK for analysis in June 2016, with first reports expected in 2017.

Interplanetary dust particles

A further important source of cosmic dust samples for laboratory studies are interplanetary dust particles (IDPs), a term given to particles collected from the Earth's stratosphere. The stratosphere is dry and comparatively clean, with terrestrial contaminants typically limited to those from the most violent volcanic eruptions and from our own activities (e.g. launching spacecraft/satellites). For more than three decades, NASA has collected dust using high-altitude planes to capture particles on sticky silicone-oil-covered Lexan plates that are exposed as they fly through the stratosphere (Brownlee 1976, 1985). Plates can be exposed for one or more flights, amassing collection times of tens to 100 hours. As a consequence of these short collection times, and the fact that particles larger than ~100 µm settle too quickly to Earth to be efficiently collected here, IDPs are typically ~10 µm in size.

As with micrometeorites, some IDPs exhibit similarities with meteorite groups and some appear to have originated from bodies not sampled in current meteorite collections. An example is the chondritic porous (CP) IDPs, particles that are porous aggregates of anhydrous, unequilibrated minerals with large quantities of organic material, which are very different to meteorites and are thought to originate from comets (Bradley 2003, figure 2d), suggesting these particles can also help to provide a more complete picture of the solar system. An advantage of such stratospheric collections is the ability to time flights to coincide with meteor showers in an attempt to capture particles whose origin is better constrained. For example, in April 2003 a collection was performed to coincide with the enhanced dust infall at Earth from dust trails associated with comet 26P/Grigg–Skjellerup (Messenger 2002). A major concern about this type of collection is the use of silicone oil, which can contaminate samples even after washing with hexane (Bradley et al. 2014). Silicon is a major rock-forming element and present within many of the minerals found in extraterrestrial materials; as a contaminant it complicates the interpretation of sample analyses.

Low Earth orbit collections

The past few decades have also seen cosmic dust collections being performed at higher altitudes, in low Earth orbit, with various dedicated and non-dedicated surfaces being exposed to space and returned for analysis in the laboratory. Dedicated collection surfaces are those with the primary purpose of collecting cosmic dust particles, such as many of those that comprised the Long Duration Exposure Facility (LDEF). LDEF was a bus-sized spacecraft whose 14 faces were exposed to cosmic dust in low Earth orbit in April 1984 and returned to Earth for analysis after 69 months. Non-dedicated collection surfaces are those with other primary functions that have been returned to Earth after maintenance, such as the solar cells of the Hubble Space Telescope (HST). In low Earth orbit, without the atmosphere to slow them down, cosmic dust particles will be travelling between 5 and 70 km s–1 (Graham et al. 2001a) – the slowest particles are likely to be space debris. The high impact speeds mean that cosmic dust samples on both dedicated and non-dedicated collection surfaces tend to comprise impact craters whose interiors may contain remnant residues of the original impacting particle.

Much research has been performed to determine whether chemical analyses by scanning electron microscopy (SEM) with energy dispersive X-ray analysis (EDX) can be used to distinguish the residues produced by natural vs anthropogenic cosmic dust in an effort to study the relative flux of these two types (Graham et al. 1997, 1999, 2001b, Kearsley et al. 2005, 2007). Although it has been shown that these can be told apart by the presence of characteristic elements (e.g. those dominated by Al or Ti are typically anthropogenic space debris, those containing Mg, Si, Fe, S and Ni are natural cosmic dust), the success of such surveys is largely dependent on the nature of the collection surface. Dedicated collection surfaces are designed to ensure that these residues stand out, but the situation can be much more complex with non-dedicated surfaces, as noted by **Anton Kearsley** (Natural History Museum/University of Kent) in his talk describing recent work analysing surfaces of a returned radiator shield from the HST Wide Field and Planetary Camera 2.

In situ analysis and sample return

Although the passive collections described above are extremely valuable, they all suffer the same shortcoming: the parent body that each individual cosmic dust particle comes from cannot be identified with complete certainty. Even when IDP collections and new micrometeorite collections have been performed to coincide with meteor showers, these particles nevertheless arrive and mix with other extraterrestrial particles prior to collection and thus there remains uncertainty in their origin. In order to obtain data on dust particles from known bodies (and thus associate dust properties with different types of solar system body) it is necessary to launch spacecraft to visit and either analyse material in situ or return samples to Earth for study.

Several missions have detected interplanetary and interstellar dust during their flight through interplanetary space, such as Pioneer 10 and 11 (Humes et al. 1974) and Ulysses (Krüger et al. 2015). However, several missions have sought to study solar system dust at its source. During its 1986 apparition, an armada of spacecraft were sent to rendezvous and investigate comet 1P/Halley. These included the Soviet Vega 1 and 2 spacecraft and ESA's Giotto probe, which imaged and performed chemical analyses of dust particles collected in the vicinity of the comet. These found that the particles were extremely fine grained and dominated by either organic-rich matter (containing carbon, hydrogen, oxygen and nitrogen) or mineral-forming elements (containing sodium, magnesium, silicon, iron and calcium) (Langevin et al. 1987) – much like the mixture of materials observed in CP IDPs and some types of micrometeorite.

Since then we have seen the in situ analysis of dust by missions including Galileo, whose impact-ionization Dust Detector analysed dust as it passed through Jupiter's gossamer ring system (Krüger et al. 2009), and Cassini, whose Cosmic Dust Analyzer instrument studied dust particles during both its flyby of Jupiter and its orbits of Saturn and its rings and moons (Srama et al. 2011). The rings of Saturn are one of the most famous dusty features of the solar system but, as well as characterizing dust particles in and around Saturn's rings, this instrument has also detected particles ejected in jets from Saturn's moon Enceladus, finding evidence for hydrothermal activity beneath its icy crust (Hsu et al. 2015).

More recently, in 2014, ESA's Rosetta mission arrived at comet 67P/ Churyumov– Gerasimenko (figure 3a). In his talk, **Andrew Morse** (Open University) described how instruments on the Philae lander were able to obtain useful data despite an unfortunate landing that left it on its side in the shadow of a cliff – the Ptolemy instrument managed to identify organics among cometary dust (Wright et al. 2015). The orbiter also carried several instruments to both image dust particles and analyse their chemistry, finding that many have similar morphologies and compositions to CP IDPs, thus strengthening the link between these particles and comets (e.g. Bentley et al. 2016).

The in situ measurements performed by spacecraft are ultimately limited by the mass constraints of the mission: they can carry only limited numbers of instruments and only certain instruments have been developed into portable versions. In order to perform a complete analysis of dust particles it is necessary to return samples to Earth. In 2004, NASA's Stardust mission flew through the coma of Comet 81P/Wild 2 (figure 3b), capturing particles leaving the cometary nucleus as they hit the aerogel and aluminium foils of the Stardust collector at 6 km s–1. The collector also returned several grains believed to be of interstellar origin (Westphal et al. 2014). The Stardust samples were returned to Earth for study in 2006, but being collected via impact has complicated the interpretation of these samples. In his talk, **Mark Burchell** (University of Kent) discussed how interpretation of these and other collections where particles suffer high pressures and temperatures as a result of high-velocity impacts (e.g. low Earth orbit collections), requires the study of impact analogues produced in the laboratory.

For Stardust, a comprehensive series of impact analogues produced by simulating collection conditions using a two-stage light gas gun and known impacting particles have enabled interpretations of original mineralogy to be made (e.g. Kearsley et al. 2006, Burchell et al. 2008, Price et al. 2010, Wozniakiewicz et al. 2012). Despite the expectation that cometary samples would contain an abundance of unprocessed outer solar system materials accreted directly from the collapsing molecular cloud, much of the material appears to have formed close to the young Sun. This suggests that large-scale radial mixing occurred in the early solar system, transporting high-temperature, inner solar system materials to the outermost regions where comets accreted.

In 2005, JAXA's Hayabusa mission briefly touched down on asteroid 25143 Itokawa (figure 3c). Although aiming to bring back larger samples, a complication during touchdown meant that the Hayabusa sample-set was limited to dust-sized grains. Despite this, since their return to Earth in

2010, these grains have revealed the asteroid to be similar to ordinary chondrites (Nakamura et al. 2011).

Astronomical observations of dust

Ground- and space-based telescopes can be used to obtain images and spectra of cosmic dust, providing details of their sizes, temperatures and even compositions. A significant advantage of such astronomical observations over in situ and laboratory studies is the sheer scale over which the observations provide information: rather than providing information on a few to hundreds of individual grains, they provide bulk data from billions of grains. Essentially, astronomical observations show us the bigger picture. They also provide us with the ability to study the evolution of dust over time by, for example, observing dust in the interstellar medium and molecular clouds and comparing with dust observations for solar systems of different ages.

Observations of diffuse interstellar bands were addressed in the talk by **Jonathan Smoker** (Very Large Telescope/European Southern Observatory), who discussed their origin based on dust particles and the reddening effect they cause. Studies of polycyclic aromatic hydrocarbons (PAHs) in the interstellar medium using the United Kingdom Infrared Telescope (UKIRT) were the subject of a talk by **Peter Sarre** (University of Nottingham), describing how the 3.3 μm and 11.2 μm emission features are being used to interpret details of their molecular size, shape, response to UV excitation, and mass and spatial distribution.

Significant observations of young stars with protoplanetary discs have also been performed in the last two decades. These studies looked at the disc compositions and crystallinity, comparing discs to similar studies of molecular clouds to determine how these materials are processed during the early stages of solar system formation (e.g. Van Boekel et al. 2004). More recent studies of the protostar HOPS-68 by the Spitzer Space Telescope have provided evidence of crystalline olivine grains in the collapsing outer regions of the star's protoplanetary disc. It has been suggested that these observations provide evidence of a large-scale transport mechanism at work. This is because crystalline materials are scarce in precursor molecular clouds; the olivine grains are therefore likely to have formed close to the star where temperatures are high enough to anneal (Poteet et al. 2011). Observations are also being made on the growth of larger objects from dust; fantastic images recently collected by the Atacama Large Millimeter/submillimeter Array (ALMA) observatory of the protoplanetary disc around the young T Tauri star HL Tauri (figure 4a), show evidence of gaps that are likely the results of particles being hoovered up by as yet invisible planetesimals (NRAO press release 2014). Stunning images have also been obtained by the HST of a disc of material containing planets around the more evolved star Fomalhaut (figure 4b). This is a cooler debris disc that is likely to be the remnants of a protoplanetary disc, or the result of continued collisions between asteroids and comets (Kalas et al. 2008). Similar circumsolar rings are associated with the planets of our solar system, superimposed on the zodiacal cloud. In his talk, **Mark Jones** (Open University) described how a recent study using data obtained by the HI-2 instrument on board STEREO highlighted the existence of such a dust ring associated with Venus (Jones et al. 2013).

Most of the interpretations of astronomical observations are impossible to test in a laboratory: conditions on the Earth are very different to those space environments we want to simulate, and the timescales involved and spatial scales required are far greater than we can accommodate. A powerful tool in the interpretation of these observations is therefore computer simulation, which allows us to test hypotheses of, for example, dust motion over several thousand years in as little as a few minutes. This allows us to vary the dust conditions (e.g. stickiness, density, temperature of the cloud etc) and see how clouds evolve. Such simulations were the topic of the talk by **Melanie Köhler** (Queen Mary University of London), who described her study of dust accretion as grains move from diffuse to denser regions of the interstellar medium (Köhler et al. 2015).

Technological advances

Over the next few decades it is likely that advances in technological capabilities will require us to reanalyse samples or re-observe objects and ultimately reassess our previous results and interpretations. For example, the study of crater residues in Stardust aluminium collector foils and samples from low Earth orbit has been extensively performed by SEM-EDX. Traditional EDX detectors are mounted to one side of the sample and consequently, when attempting to obtain data from the non-flat topography of craters, produce data that exhibit shadowing; elemental maps over craters exhibit shadows, collecting data for only a thin crescent inside the crater on the side opposite the detector. The new Bruker XFlash Quad silicon drift EDX detector, described in **Anton Kearsley's** talk, is designed to be fixed directly above the sample, allowing X-rays originating from throughout a crater to be detected. It thus produces maps that provide a complete picture of the contents of craters. With this new capability, we may discover that our previous conclusions about these impacted surfaces are mistaken; for example, it was concluded that only ~50% of observed craters on LDEF contained detectable impactor residues (Hörz & Bernhard 1992), but this may well increase. Similarly, new telescopes such as the proposed Space Infrared Telescope for Cosmology and Astrophysics (SPICA), described in a talk by **Dave Clements** (Imperial College London), will aim to provide complementary data to existing telescopes at improved resolutions.

Comparing results

Comparing the different methods of studying cosmic dust makes one thing clear: while each has the potential to provide excellent information, it is only by combining these studies and comparing results that we can attempt to understand cosmic dust more fully. For example, dust samples in the laboratory can be analysed by a huge suite of instruments to determine the history of individual particles and conditions on its parent body, but these details alone cannot be linked to a parent body type (e.g. comets or asteroids). Only through direct sampling, or observations, of dust-generating bodies can we try to link these analyses with parent body types.

This was demonstrated in the talk by **Mike Zolensky** (NASA/Johnson Space Center) who described how the results from samples of comet 81P/Wild 2 are forcing a re-examination of pre-existing assumptions about IDPs. Prior to the return of Stardust, it was anticipated that the mission samples would be very similar to CP IDPs because these were generally thought to also come from comets. However, as the samples were analysed it became clear this was not the case; the samples had much in common with meteorites thought to sample asteroids (Ishii et al. 2008). In comparison, the recent Rosetta images and analyses of cometary particles appear to support the idea that CP IDPs are from comets. These comparisons also serve to remind us that the distinction between comets and asteroids may not be black and white, and that we may need to re-examine IDP and micrometeorite samples with that in mind. This idea was echoed in the talk by **John Bridges** (University of Leicester), where it was noted that, despite the general view of comets as bodies that have remained frozen and inactive since they accreted, various minerals thought to require the prolonged presence of liquid water have been identified in Stardust samples.

Comparing data obtained from micrometeorites, IDPs, low Earth orbit samples, in situ analyses, sample-return missions and astronomical observations is therefore valuable and vital to the successful investigation of cosmic dust, and to understanding the formation and evolution of solar systems and the bodies they contain. Furthermore, as indicated in the brief discussion above, the studies themselves are leading to significant changes in our understanding of the origin and distribution of solid matter around and between stars.

AUTHOR

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Figure 1: Zodiacal light, a phenomenon observed in the night sky caused by the scattering of sunlight by interplanetary dust. (ESO/Y Beletsky)

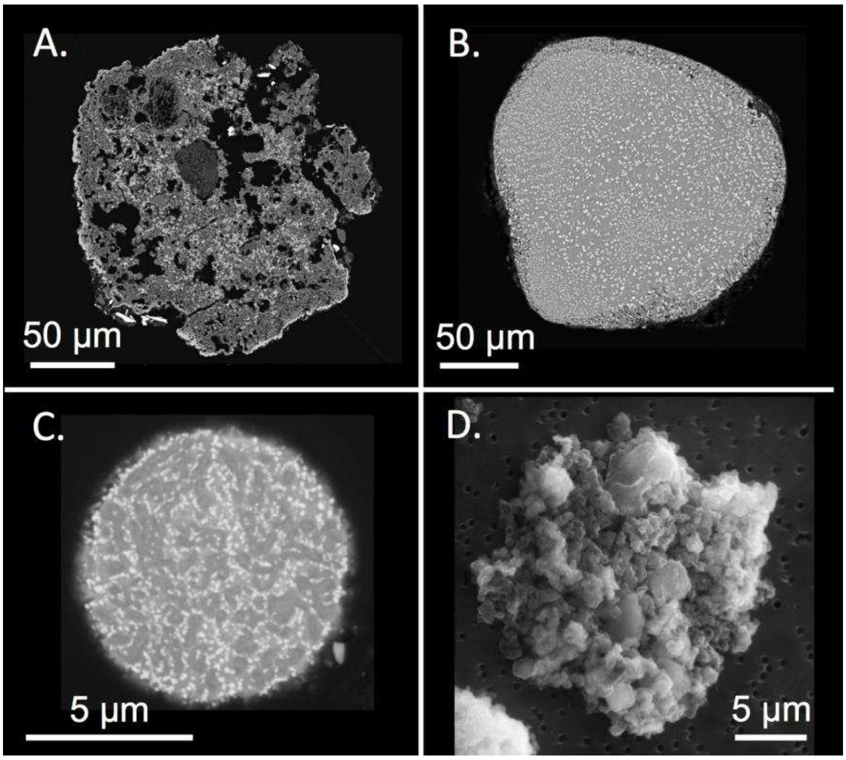

Figure 2: SEM images of examples of cosmic dust collected at Earth. (a) Cross section through micrometeorite exhibiting a magnetite rim from the South Pole water well collection (S Taylor). (b) Section through cryptocrystalline S-type cosmic spherule from the Larkman Nunatak collection (M Genge and M van Ginneken). (c) Section through micrometeorite candidate from Kwajalein collection exhibiting properties consistent with cryptocrystalline S-type cosmic spherules (P Wozniakiewicz). (d) Chondritic porous interplanetary dust particle (CP IDP) collected in the stratosphere (M. Zolensky/NASA/JSC).

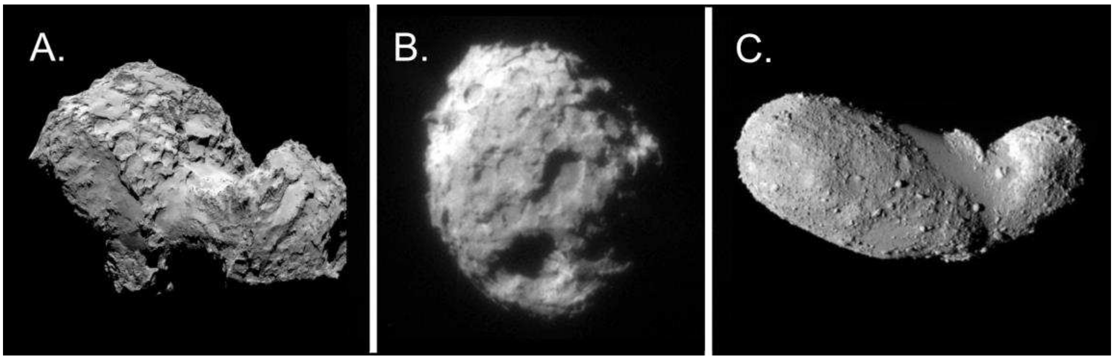

Figure 3: (a) Comet 67P/Churyumov–Gerasimenko visited by ESA's Rosetta mission (ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA). (b) Comet 81P/Wild 2 visited by NASA's Stardust mission (NASA). (c) Asteroid 25143 Itokawa visited by JAXA's Hayabusa mission (JAXA).

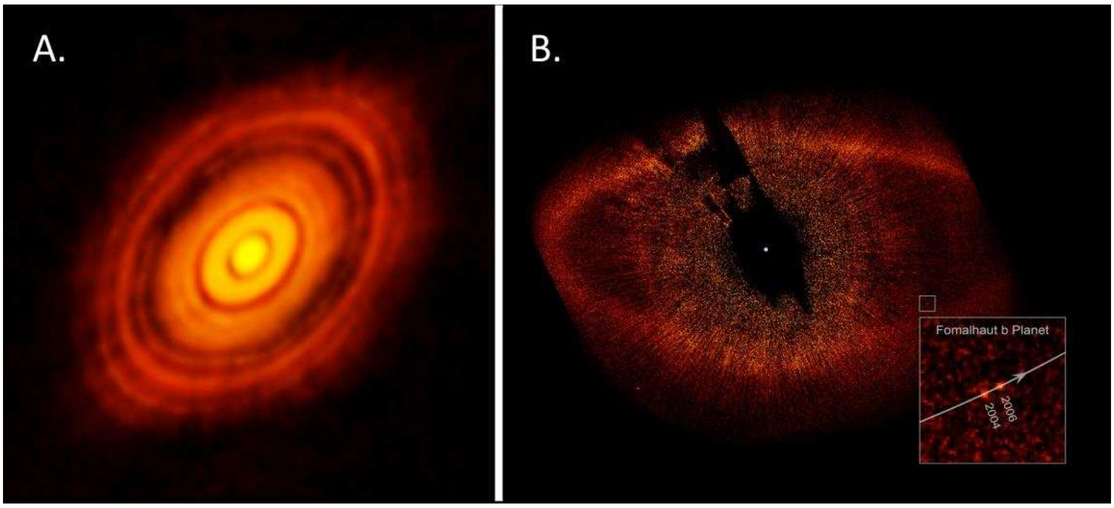

Figure 4: (a) ALMA image of the protoplanetary disc around the young star HL Tauri showing gaps indicative of clearing by planetesimals. (ALMA [ESO/NAOJ/NRAO]). (b) HST image of the disc and planets identified around Fomalhaut. (NASA, ESA, P Kalas, J Graham, E Chiang, E Kite [Univ. California, Berkeley], M Clampin [NASA Goddard Space Flight Center], M Fitzgerald [Lawrence Livermore National Lab], and K Stapelfeldt and J Krist [NASA Jet Propulsion Lab])

Table 1: Methods of studying cosmic dust

method	**samples**
studying samples arriving at or passing through the vicinity of the Earth in the laboratory	micrometeorites collected at the surface
	interplanetary dust particles collected in the stratosphere
	natural and anthropogenic cosmic dust collected in low Earth orbit from a variety of space missions (e.g. LDEF, HST solar panels etc)
studying dust *in situ*	interstellar and interplanetary dust (e.g. Pioneer 10 and 11, Ulysses, Cassini)
	cometary (e.g. Vega 1, Vega 2, Giotto, Stardust, Rosetta)
	jovian system dust (e.g. Galileo, Cassini)
	saturnian system dust (e.g. Cassini)
collecting dust at source and returning dust to Earth for analysis	cometary dust (Stardust)
	asteroidal dust (Hayabusa)
astronomical observations	solar system
	extrasolar systems
	molecular cloud
	interstellar medium