Interstellar and Pre-Solar Grains in the Galaxy and in the Solar System

P. Frisch, E. Grün and P. Hoppe

Department of Astronomy and Astrophysics, University of Chicago, Chicago, USA
Max-Planck-Institut für Kernphysik, Heidelberg, Germany and
Hawaii Institute of Geophysics and Planetology, Honolulu, USA
Max-Planck-Institut für Chemie, Mainz, Germany

Introduction

Dust grains represent an important repository of cosmic matter, tracing stages of stellar evolution in our Galaxy. Three interdisciplinary workshops at ISSI in 1997 and 1998 studied dust grains at complementary phases of their life cycle. At these workshops the properties of astronomical interstellar dust grains (ISDG) were compared with in-situ ISDG data and pre-solar grains found in meteorites. The astronomical dust data yield grain composition and size distribution through optical, infrared (IR), and ultraviolet (UV) absorption and emission properties. In contrast, in-situ spacecraft data provide the ISDG mass distribution after correction for heliospheric interactions. Precise laboratory studies of presolar grains from meteorites yield the composition and origin of the stardust that parented the ISDGs. Bringing these views together at ISSI provided a new viewpoint of the mass distribution of ISDGs impinging on the Solar System, the gas-to-dust mass ratio and grain composition in the local interstellar cloud, grain formation in stellar atmospheres, destruction in the interstellar medium (ISM), and the composition of pre-solar versus ISDGs.

It became clear during the ISSI meetings that relating pre-solar and interstellar grains requires allowance for grain processing in space, including radiative damage, alteration, spallation, reheating, and exposure to additional compounds in dense interstellar clouds. Ed Anders noted: "There is no real contradiction between the meteoritic and astronomical data on grains. The vast majority of interstellar grains are reprocessed, homogenized [and fragmented]. The pristine circumstellar grains are chance survivors of a stochastic process that destroyed all but $10^{-4}$ of them." These same processes convert crystalline silicates detected in stellar atmospheres to amorphous silicates seen in interstellar space.

The Solar System and Beyond: Ten Years of ISSI
Several publications arose from these ISSI workshops, including a paper in the Astrophysical Journal, and a special issue of the Journal of Geophysical Research (JGR), which contains 17 articles delving into different aspects of these grain populations (http://www.agu.org/journals/ja/ja0005/ja105_5.html). In the following sections, we outline the state-of-knowledge at the present time.

**Galactic Dust**

Dust in space was discovered towards the beginning of the 20th century, with dark dust clouds dominating observations (Fig. 1). The early research of Mayo Greenberg, an active participant in the ISSI workshops, helped lay the foundations for our understanding of interstellar dust grains. A consistent theoretical description of interstellar dust requires a grain mixture that varies according to the relative amounts of diffuse and dense interstellar clouds. The Local Interstellar Cloud (LIC) is a low density weakly ionized interstellar cloud \([n(H)\sim 0.3 \, \text{cm}^{-3}, \, n(e)\sim 0.1 \, \text{cm}^{-3}]\) showing larger abundances of heavy refractory

![Figure 1. The heliosphere viewed against the plane of the Milky Way towards the Galactic Centre direction. Interstellar dust grains in dark clouds are seen to obscure background starlight in this composite Milky Way Galaxy image based on an A. Mellinger photograph and stars in the Hipparcos database. Dust is also found in the tenuous transparent interstellar cloud around the heliosphere. (Visualization by A. Hanson, P. Fu and P. Frisch, based on T. Linde’s MHD model of the heliosphere embedded in a magnetized diffuse interstellar cloud. 3D star positions from the Hipparcos satellite.)](image)
elements such as Fe, Ca, Mg, and Si in the gas-phase than cold dense interstellar clouds. Theoretical models of the lifetimes of interstellar dust grains indicate that LIC abundances are explained by grain destruction in violent interstellar shock fronts with velocities of 50 - 100 km s⁻¹, which shatter grains and vaporize a small fraction of the refractory elements in the grain core. The interaction of galactic dust with the heliosphere depends on the grain mass and charge. The smallest ISDGs (radii ≤ 0.05 µm) are trapped by the interstellar magnetic field and diverted around the heliosphere. Larger grains penetrate the heliosphere where they are measured by interplanetary spacecraft.

**Astronomical grain populations**

The ISSI workshops on interstellar dust inside and outside of the heliosphere, and pre-solar grains, led to the first detailed comparisons between these diverse dust data. The properties of ISDGs are ordinarily determined from observations of clouds 100 to 10 000 times denser than the LIC. Starlight is scattered, extinguished, and polarized by interstellar dust grains in the diffuse ISM, where gas densities are $n_{\text{gas}} < 100$ cm⁻³. An understanding of grain sizes in the LIC is required to interpret data on grains inside the heliosphere, and this data is provided by optical data from more distant stars, which reveal a power-law dependence for grain sizes (proportional to $a^{-3.5}$, for grain radii $a$ and $a = 0.005 - 0.25$ µm). The raw grain material required to explain observed spectral features in the ultraviolet (such as the extinction bump at 2175 Å) and infrared (such as the emission features at 9.8 µm, 18 µm, and 3.3 - 11.4 µm) includes a mixture of tiny carbonaceous particles (either PAH's or graphite, $a < 50$ Å), and amorphous silicates. Denser clouds and ionized regions exhibit a notable lack of the tiny PAH grains, which appear to produce the far UV extinction, and infrared observations of molecular clouds and in-situ observations of dust inside the Solar System show that larger dust grains ($a~1$ µm) are present.

The low-density ISM near the Sun does not have enough dust for UV or infrared detection. However, Ulysses and Galileo discovered a population of large grains with $a~1$ µm. One puzzle is that Weingartner & Draine found that these large grains are not required to model the size distributions of the tiny carbonaceous grains causing the infrared emission and the 2175 Å extinction bump. Although grain models are still uncertain, one conclusion of the ISSI workshops is that interstellar dust and gas may decouple over the lifetime of intermediate velocity clouds such as the LIC, which itself appears to have originated as a fragment of an expanding superbubble shell generated by stellar evolution in the Scopius-Centaurus Association.

Classical interstellar dust grains are aligned by interstellar magnetic fields and polarize background starlight. One of the earliest tracers of very nearby interstel-
lar dust was polarized starlight observed for stars towards the galactic centre, which we now know corresponds with the location of most of the mass of the ISM within 30 pc. Comparison between the wavelength distribution of polarized starlight and broad unexplained optical interstellar absorption features known as the diffuse interstellar bands (DIBs) establishes that the DIB features are carried by the tiny grains which most likely are PAHs.

**Interstellar dust grains in the LIC**

One of the most fundamental issues in astrophysics is the chemical composition of matter in our Universe. One of the results of our ISSI dust workshops was a new way to evaluate the ratio of the masses of the gas versus the dust proportions ($R_{g/d}$) of a diffuse interstellar cloud. If the total chemical composition of a cloud is known, and combined with abundances of elements observed in the gas phase, in principle both $R_{g/d}$ and the grain composition can be determined. This is the “missing-mass argument”, and follows from a premise that the original cloud material remains together as either gas or dust throughout the cloud lifetime; Classical ISM theory presumes that the assumed cloud abundance pattern is solar, but data on elements such as Kr, O, S, suggest lower intrinsic abundances at about ~80% solar that are reminiscent instead of the abundances of much younger B-stars. We applied these missing-mass arguments to the LIC data and found $R_{g/d}$~170 if the LIC chemical composition is solar, or $R_{g/d}$~600 if it is comparable to B-star abundances. However, when we use directly the Ulysses and Galileo data we find that $R_{g/d}$<110 (the upper limit is used because small grains are excluded from the heliosphere). The difference between values obtained from missing-mass arguments versus in situ data indicates that larger ISDGs may decouple somewhat from the gas over the small spatial scales.

The warm (6400 K) LIC shows higher abundances of refractory elements such as Ca and Fe in the gas phase than normal for cold clouds in the Milky Way Galaxy disk. Virtually all Fe in a cold cloud is in grains, while ~20% of the Fe in the warm LIC is in the gas phase. Grain destruction also preferentially erodes the silicate-rich mantle overlaying grains in dense clouds. Since the large grains remain in the LIC, either grain destruction is incomplete, or large grains are themselves replenished in space. The LIC grain composition inferred from missing-mass arguments favours a mixed oxide/silicate composition.

**Connecting stardust and interstellar dust**

Notable among the JGR special section papers is an exploration of the condensation of dust grains in stellar atmospheres, and a comparison of this grain mineralogy with interstellar dust composition. This investigation represents the first effort to theoretically simulate the composition of “stardust” in terms of the condensation...
pattern in stellar outflows such as asymptotic giant branch (AGB) star atmospheres, and it successfully reproduced interstellar abundances of the three elemental groups most depleted onto interstellar dust grains in cold clouds. For an initial atmosphere with solar composition, the predicted condensations of Ca and Ti (the most heavily depleted ISM elements) are consistent with the formation of Ca- and Ti-rich oxides at high temperatures (>1500 K). Moderately depleted elements (Cr, Co, Fe, V, Ni) condense as olivine and metal alloys at 1250 - 1500 K. The mildly depleted elements Mg and Si condense first as olivine above 1350 K (Mg/Si = 2), but convert to orthopyroxene at lower temperatures (Mg/Si = 1) as more Si condenses out. Ebel also found that most Fe condenses into metals, with minimal Fe in silicates. This silicate condensation pattern is consistent with the preferential erosion of Si-rich grain surfaces seen in the ISM. The correspondence between the three depletion groups in the ISM and condensation phases in stellar outflows suggests that refractory element abundance patterns of interstellar dust grains are related to grain formation in stellar atmospheres.

Interstellar Dust in the Solar System

The only direct observation of ISDGs close to the Sun is the weak polarization of 36 Oph (~6 pc) from magnetically aligned grains. From observations of nearby interstellar gas we know that the Solar System passes currently through a shell of material that is located at the edge of the Local Bubble. It emerged from the interior of this bubble within the past 10^5 years. The local interstellar cloud may have been ejected by supernova explosions from the molecular clouds and star-forming regions in the Scorpius-Centaurus Association. It is clear that in-situ sampling of dust from this cloud would greatly help us to understand the nature and processing of dust in various galactic environments, and cast new light on the chemical composition and homogeneity of the interstellar medium.

More than a decade ago, interstellar dust was positively identified inside the planetary system. After its flyby of Jupiter, the dust detector on board the Ulysses spacecraft detected impacts predominantly from a direction that was opposite to the expected impact direction of interplanetary dust grains (Fig. 2). It was found that, on average, the impact velocities exceeded the local Solar System escape velocity, even if radiation pressure effects were neglected. Subsequent analysis showed that the motion of the interstellar grains through the Solar System was parallel to the flow of neutral interstellar hydrogen and helium gas, both traveling at a speed of 26 km/s. The interstellar dust flow persisted at higher latitudes above the ecliptic plane, even over the poles of the Sun, whereas interplanetary dust is strongly depleted away from the ecliptic plane.
Since that time, Ulysses has monitored the stream of interstellar dust grains through the Solar System at higher latitudes. In mid-1996, a decrease by a factor 3 in the interstellar dust flux density was observed\cite{17}. This decrease was attributed to the increased filtering of small grains by the solar-wind magnetic field during solar-minimum conditions\cite{18}. Since early 2000, Ulysses has detected the earlier higher interstellar-dust flux levels again\cite{19}. Interstellar dust had initially been identified outside 3 AU up to Jupiter’s distance. However, refined analyses\cite{20,21} showed that both Cassini and Galileo recorded several 100 interstellar grains in the region between 0.7 and 3 AU from the Sun. Even in the Helios dust data, interstellar grains were identified down to 0.3 AU distance from the Sun\cite{21}.

**Size distribution**

The radii of clearly identified interstellar grains range from 0.05 \(\mu m\) to above 1 \(\mu m\) with a maximum at about 0.3 \(\mu m\). The deficiency of small grain masses \(a < 0.3 \mu m\) compared to astronomically observed ISD is not solely introduced by the detection threshold of the spacecraft instruments, but indicates a depletion of small interstellar grains in the heliosphere.
There are significant differences in the particle sizes that were recorded at different heliocentric distances. Mass-distribution measurements revealed a lack of small (<0.3 \( \mu m \)) ISD grains inside 3 AU heliocentric distance\(^{22}\). Measurements by Cassini and Galileo in the distance range between 0.7 and 3 AU showed that interstellar particles were bigger than 0.5 \( \mu m \), with increasing masses closer to the Sun. The flux of these big particles did not exhibit temporal variations due to the solar-wind magnetic field like the flux of smaller particles observed by Ulysses. The trend of increasing masses of particles continues, as demonstrated by Helios measurements, which recorded particles of ca. 1 \( \mu m \) radius down to 0.3 AU. These facts support the idea that the ISDG stream is filtered by the radiation pressure as well. It is concluded that interstellar particles with optical properties of grains consisting of astronomical silicates or organic refractory materials are consistent with the observed radiation pressure effect\(^{23}\).

Recently, even bigger (40 \( \mu m \)) interstellar meteors have been reliably identified by their hyperbolic speeds in radar meteor observations\(^{24-26}\). The flow direction of these larger particles varies over a much wider angular range than that of small (sub-micron-sized) grains observed by spacecraft. Baggaley\(^{25}\) identified a general background influx of extra-Solar System particles from southern ecliptic latitudes with enhanced fluxes from discrete sources. Meteor observations with the Arecibo radar are more sensitive than the above: Meisel et al.\(^{26}\) found a flux of several micron-sized interstellar meteor particles radiating from the direction of the Geminga supernova.

There are important consequences from the big particle population in the local diffuse interstellar medium. While the particles observed by spacecraft couple to the interstellar medium on length scales of < 1 parsec via electromagnetic interactions, more massive grains couple to the gas over much longer scales of 100 to 1000 pc\(^{15}\). Therefore, big interstellar meteor particles travel unaffected over much longer distances and may come directly from their source region.

Pre-solar Grains in Meteorites and IDPs

Historical background and astrophysical implications

Our Solar System formed from the collapse of a molecular cloud about 4.57 billion years ago, possibly triggered by a supernova (SN) explosion\(^{27-28}\). The release of gravitational energy led to the evaporation of a large fraction of the dust grains in the molecular cloud and much of the nucleosynthetic memories carried by these grains was erased by chemical and isotopic equilibration. A small fraction of the dust grains, however, survived in relatively cool regions of the solar nebula and were incorporated into planetary bodies. In comets and small
Pre-solar grains are recognized by their anomalous isotopic compositions. The first pre-solar minerals, namely diamond and silicon carbide (SiC), were isolated from primitive meteorites in 1987 by Ed Anders and co-workers at the University of Chicago. The noble gases played a key role in the identification of carbonaceous pre-solar grains, not only for diamond and SiC, but also for graphite, which was discovered several years later. In the following decade, presolar oxides such as corundum (Al₂O₃) and spinel (MgAl₂O₄) and silicon nitride (Si₃N₄) were found in acid-resistant residues from primitive meteorites by single-grain isotopic studies in the ion microprobe. Pre-solar silicates (variable composition) were identified only recently. The search for them was complicated because the harsh chemical treatments used to prepare acid-resistant residues destroy silicates. The invention of the new-generation NanoSIMS 50 ion microprobe makes it now possible to search in slices of meteorites and IDPs for in-situ pre-solar dust with sizes in the sub-micrometre range, and the application of this method has been essential for the discovery of pre-solar silicates. Examples of pre-solar grains separated from meteorites are shown in Figure 3.

The laboratory study of pre-solar grains has opened a new window in astronomy. It was quickly realized that the pre-solar grains must have formed around evolved stars (Fig. 4) or in the ejecta of SN explosions, i.e. they represent a sample of stardust that can be analyzed with high precision in the laboratory. Isotopic and structural studies have provided a wealth of information on stellar nucleosynthesis and evolution, mixing in SN ejecta, Galactic chemical evolution, and the cosmic record of the building blocks of the solar system.
grain formation in stellar environments, and the types of stars that contributed dust to our Solar System.

Table 1 lists pre-solar minerals, their abundances, sizes, and stellar sources. In the following sections we will briefly summarize the isotopic properties and stellar sources of presolar silicon carbide, graphite, silicon nitride, corundum, spinel, and silicates. More detailed information can be found in recent review papers31,32.

Table 1. Pre-solar minerals in meteorites and IDPs

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Abundance (ppm)</th>
<th>Size (µm)</th>
<th>Stellar source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>1000</td>
<td>0.002</td>
<td>Supernovae</td>
</tr>
<tr>
<td>SiC mainstream</td>
<td>10</td>
<td>0.2-10</td>
<td>AGB stars</td>
</tr>
<tr>
<td>SiC X</td>
<td>0.1</td>
<td>0.2-10</td>
<td>Supernovae</td>
</tr>
<tr>
<td>Graphite</td>
<td>1</td>
<td>1-10</td>
<td>Supernovae, AGB stars</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>0.001</td>
<td>1</td>
<td>Supernovae</td>
</tr>
<tr>
<td>Corundum</td>
<td>0.1</td>
<td>0.2-5</td>
<td>RGB &amp; AGB stars</td>
</tr>
<tr>
<td>Spinel</td>
<td>10</td>
<td>0.2-5</td>
<td>RGB &amp; AGB stars</td>
</tr>
<tr>
<td>Silicates in IDPs</td>
<td>1000</td>
<td>0.1-1</td>
<td>RGB &amp; AGB stars</td>
</tr>
<tr>
<td>Silicates in meteorites</td>
<td>100</td>
<td>0.1-1</td>
<td>RGB &amp; AGB stars</td>
</tr>
</tbody>
</table>

Silicon carbide, graphite, and silicon nitride
Silicon carbide is the best-studied pre-solar mineral phase. Based on the isotopic compositions of C, N and Si and the abundance of radiogenic $^{26}$Mg (from the radioactive decay of $^{26}$Al) SiC was divided into six different populations. Most abundant are the mainstream grains (about 90% of the total SiC), which are believed to have formed in the winds of 1-3 $M_\odot$ AGB stars. Such stars are also the source for some of the graphite grains.

The isotopic compositions of a rare sub-group of pre-solar SiC grains, the so-called X grains, and of most graphite and Si$_3$N$_4$ grains show imprints of advanced stellar nucleosynthesis, and those grains are most likely from SN. The presence of the decay products of short-lived radioactive $^{44}$Ti (half-life 60 years) and $^{49}$V (half-life 11 months) indicates that the grains incorporated matter from the innermost regions of the exploding star and that grain growth occurred on a time scale of several months.

Corundum, spinel and silicates
Similar to the light elements in SiC and graphite, the O-isotopic compositions of pre-solar corundum and spinel range over many orders of magnitude. The O-isotopic signatures suggest that most of these grains formed in the winds of 1-4 $M_\odot$, red giant branch (RGB) and AGB stars. Grains from SN are apparently rare. To
date, only one corundum grain (out of ~400 identified pre-solar corundum and spinel grains) shows a strong isotopic enrichment in $^{16}$O, the predominantly expected signature of SN grains.

Among the pre-solar silicates identified to date are olivines, pyroxenes, and so-called GEMS (glass with embedded metal and sulphides). Abundances of pre-solar silicates are much higher in IDPs than in primitive meteorites (Table 1). The O-isotopic signatures of most grains are compatible with those of the majority of the pre-solar corundum and spinel grains, suggestive of formation in RGB and AGB stars. Similar to SiC and the refractory oxides, SN grains are apparently rare among pre-solar silicates (one out of ~50 identified pre-solar silicate grains).

Figure 4. Hubble Space Telescope image of the Cat’s Eye Nebula. The evolved AGB star (centre) ejected its mass in a series of pulses at 1500 year intervals. These convulsions created concentric dust shells, making a layered, onion-skin structure around the star (ESA, NASA, HEIC and the Hubble Heritage Team, STScI/AURA).
Interstellar and Presolar Grains in the Galaxy and Solar System

Outlook

Once it became evident that galactic ISDGs are accessible to in-situ detection and even to sample-return to Earth, the Stardust mission was proposed to analyze and return samples of ISDGs together with samples of cometary dust. In January 2004, Stardust made a fast flyby of comet Wild 2. En route to the comet, and on the return path to Earth, Stardust collected interstellar dust and analyzed it with the Cometary and Interstellar Dust Analyzer instrument, CIDA. This instrument provided the first high-mass-resolution analyses of a few tens of presumably interstellar grains. CIDA is a time-of-flight mass spectrometer with a mass resolution $M/\Delta M > 100$ that analyses ions generated by dust particles that impact a target at speeds of 20 to 40 km/s. It was concluded that the main constituents of interstellar grains are organic with a high oxygen and low nitrogen content. They suggest that polymers of derivatives of the quinine type are consistent with all impact ion spectra recorded. Analyses of the returned samples will provide more information on the composition of ISDGs.

Based on the experience gained by previous in-situ dust measurements in space, a new approach of accurate dust trajectory measurement (a few percent in speed and a few degrees in angle) together with high-resolution chemical analysis of the same interstellar grain is being developed. Recent instrument developments allow us to combine sensors of these capabilities into a single dust telescope, designed for being carried into space by a dust observatory spacecraft in order to measure the composition of large numbers of ISDGs in interplanetary space. Despite the great advances made in the last years in the understanding of the heliospheric dust environment, there remain many important questions to be answered. Significant compositional information will be gained from future in-situ measurements, but even more can be learned if this dust is collected and brought to the laboratory, where the most advanced instrumentation can be used for its analysis. Sample-return from Earth orbit is, of course, much easier than sample return from distant worlds. However, in order to separately collect interplanetary and interstellar dust in Earth orbit, a preceding detailed analysis of the various dust-flow components by a dust telescope is necessary.

The chemical and isotopic compositions and physical properties of ISDGs provide important information on stellar evolution and nucleosynthesis, the physics and chemistry of the interstellar medium, and on Solar System formation and evolution. Precise data on interstellar grains inside our heliosphere offers the potential to revolutionize our understanding of the Milky Way Galaxy.
References

5. A. Jones, in Ref. 2, p. 10257.
25. W.J. Baggaley, in Ref. 2, pp. 10353.
35. E. Grün et al., in Ref. 2, p.10403.
36. P. Frisch would like to thank NASA for support through grants NAG 5-13107 and NAG 5-11005.