Laboratory Astrophysics of Cosmic Dust

IDMC, Pune, India, November 2011
Motivation
Cosmic Dust Studies

• Dust extinction, polarization, spectroscopy, continuum emission as diagnostic tools
  (Optical depth, mass, magnetic fields, temperature, chemistry, growth processes, mixing, …)

• Dust: Thermal, dynamical, and chemical structure

• Interesting structural and optical behaviour
  (Tunneling processes at low temperatures)
Dust continuum data

Modelled by ray tracing

Nielbock et al. 2011, in prep. Herschel/EPOS project
Example: Spectrum of forsterite particles at different temperatures

Flux
Laurent et al. (2000)
How to interpret SEDs at long wavelengths?

- Presence of very cold dust
- Dust mass estimates
  (protoplanetary disks, molecular cores, galaxies, quasars, …)
- General characterization of spectral energy distributions

Linz et al. (2010)
Photoelectric heating

Bakes and Tielens (1994)
The Facts

- Silicates and carbonaceous ISM dust
- Broad size distribution
- Additional materials in circumstellar envelopes (carbides, nanodiamonds, fullerenes, …)
- Molecular ices in cold clouds
- Grain growth in disks
- Crystalline silicates and molecular ices in disks

Silicates: Henning, ARAA, 48, 21, 2010
Carbonaceous Solids: Jäger et al., EAS Publ. Ser. 46, 293, 2011
Dust emission spectrum

Fig. 4. Dust emission spectrum. Observations (crosses) pertain to the “cirrus” interstellar diffuse medium (see Table 1 and text). The horizontal bars represent the filter width used in the observations (given in Table 1). The model resulting spectrum (continuous line) is the sum of the three components that are PAHs, VSGs, and BGs.

Désert, Boulanger & Puget (1990)
More to come: Compiègne et al. (2011)
Dust emission spectrum
Dwarf Galaxy NGC 1569
(Low-metallicity Environment)

Galliano et al. 2003
Basic Types of Dust Mixtures

Stardust
Original dust formation
UV/cosmic ray processing; Modification by shocks
Surface chemistry
Ice mantles
Coagulation

Interstellar Dust

Molecular Cloud Dust

Protostellar Dust

Interplanetary Dust

Time

\[
\frac{dM_{\text{stardust}}}{dt} \sim 0.005 \, M_{\text{sun}}/\text{yr}, \quad \text{Gas: } \sim 1.2 \, M_{\text{sun}}/\text{yr} \quad (\text{Draine 2009})
\]

(Type II SN 1987a  ~8x10^{-4} M_{\text{sun}}  Ercolano et al. 2007
SN 2003gd  ~2x10^{-2} M_{\text{sun}}  Sugerman et al. 2006)

\[
M_{\text{stardust}}/M_{\text{ismdust}} \sim 1.6 \times 10^6 \, M_{\text{sun}}/2.5 \times 10^7 \, M_{\text{sun}} \sim 0.06
\]

Dorschner & Henning (1995)
Dust in the Diffuse ISM

No evidence for crystalline silicates in the diffuse ISM (<2%, e.g., Li & Draine 2001, Jäger et al. 2003, Kemper et al. 2004)

Amorphization by cosmic rays/shock processing in ISM/re-condensation of amorphous silicates in the ISM (Jäger et al. 2003)

3.4 micron absorption feature – aliphatic hydrocarbons (Pendleton & Allamandola 2002)
Amorphization easier for Fe-rich silicates

henning; 10.08.2005
Comparison of the 10 \( \mu m \) Si-O stretch band

Spectral ambiguity ….

A  GEMS in IDP L2011*B6
B  Elias 16
C  Trapezium
D  DI Cep (T Tauri star)
E  \( \mu \) Cep (M supergiant)

GEMS:
(Mg+Fe)/Si~0.7 (Keller & Messenger 2004)
Mg/Si=0.6 and Fe/Si=0.4 (Ishii et al. 2008)

Bradley et al. (1999), Chiar & Tielens (2006), van Breemen et al. (2011)
Crystalline Revolution (ISO and Spitzer)

AFGL 4106

T=100 K

Jäger et al. (1998)
IR Properties of Silicates – Amorphous vs. Crystalline Structures
IR Properties of Silicates – Amorphous vs. Crystalline Structures

- **10 µm band due to Si-O stretching; position depends on level of SiO$_4$ polymerization** (e.g. band shifts from 9.0 µm for SiO$_2$ to 10.5 µm for Mg$_{2.4}$SiO$_{4.4}$ – Jäger et al. 2003)

- **18 µm band additionally broadened** (coupling of the Si-O bending to the Me-O stretching vibration)

- **Crystalline silicates: Bands beyond 20 µm caused by translational motion of metal cations within the oxygen cage and complex translations involving Me and Si atoms**
Laboratory Investigations of Cosmic Dust

- Interplanetary dust particles and stardust in meteorites
- Optical properties of cosmic dust analogues
- Formation and modification of dust grains

EELS – Fe (red), Mg (green), C (blue); J. Bradley/H. Ishii

MPIA Jena
He droplet experiment
## Stardust in primitive meteorites and IDPs

<table>
<thead>
<tr>
<th>Material</th>
<th>Concentration</th>
<th>Size</th>
<th>Star Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite</td>
<td>10 ppm</td>
<td>1-20 µm</td>
<td>Novae, SN, AGB</td>
</tr>
<tr>
<td>Diamond</td>
<td>1400</td>
<td>0.002</td>
<td>SN(?)</td>
</tr>
<tr>
<td>SiC</td>
<td>14</td>
<td>0.3-20</td>
<td>AGB (mainstream), SN</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.01</td>
<td>0.5-3</td>
<td>Red giants, AGB, SN</td>
</tr>
<tr>
<td>Si₃N₄</td>
<td>0.002</td>
<td>1</td>
<td>SN</td>
</tr>
</tbody>
</table>
Onion-like presolar „graphite“ particle - Murchison meteorite

Clayton et al.
Detection of nanodimanonds in unprocessed Allende

Banhart et al. (1998)
Silicates from Space

- 3 Olivine grains
- 4 Pyroxene grains
- 3 Glass-like grains

AGB or RGB origin

Hoppe et al. 2005

(see also Messenger et al. 2003, Vollmer et al. 2008, 2009)
Why does interstellar dust exist?

- Dust destruction in diffuse ISM more efficient than production by AGB stars (see Jones & Nuth 2011)
- SN dust production rate seems to be very low
- „Homogeneous“ dust models (Draine & Lee) vs. core-mantle models (Greenberg) vs. „inhomogenous dust“ (Mathis)
- What is the nature of the VSGs?
- Why don´t we see SiC grains in the diffuse ISM?
Grain Sizes – From „Nano to Micro“

Coronene  Carbon Onion  Soot Particle

- **Coronene**
  - 36 atoms
  - 1 nm

- **Carbon Onion**
  - $10^5$ atoms
  - 15 nm

- **Soot Particle**
  - $10^7$ atoms
  - 200 nm
Reactivity of carbonaceous surfaces

- Agglomerated carbon particles provide large surface area
- Curved carbon structures are very reactive (mechanical tension)
- Curved carbon structures have larger number of docking sites than graphite
- Carbon onions: „Production“ and „Absorption“ of electrons
Formation of Dust

Grain formation experiments under high-T conditions

HT (≥3500 K): Very small fullerene-like carbon grains
LT (≤1700 K): Synthesis of PAH-based structures

Grain formation experiments under low-T conditions

Nuth & Moore (1989): Silicate material from molecular precursors
Dartois et al. (2005): Formation of HAC polymers produced by UV photolysis at low T
Transition from Carbon Clusters to Solid Particles
Non-crystalline disordered carbons

Soot Particles (without hydrogen/oxygen):
Curved and closed structures or polycrystalline materials

Soot Particles (with hydrogen):
Smaller grains preferably formed: Curved structures

Arc discharges, laser ablation, thermal sublimation methods, sputtering, laser pyrolysis, combustion
Gas-phase condensed soot particles

- Image 1: Structure of soot particles with a diameter of 20 nm.
- Image 2: Cross-sectional view with a length of $L_a$.
- Image 3: Side view with a length of $L_c$. 

Scale bar: 20 nm
Grain formation at high temperatures

HT ($\geq 3500$ K): Very small fullerene-like carbon grains

LT ($\leq 1700$ K): Synthesis of PAH-based structures

Jäger ea. 09
Soot formation Pathways
LT condensation process $T \leq 1700$ K

Soot grains & PAHs
or only PAHs as condensates

$\bar{\Omega}L_a = 2.2$ nm
$(C_{110}H_{32}, 1352\text{Da})$

max. $L_a = 3.0$ nm
$(C_{222}H_{42}, 2700\text{Da})$
Soot formation pathways

HT Condensation Process $T \geq 3500$ K

Fullerene-like carbon seeds & fullerenes

$C_{240}@C_{60}$

Haberland, Clusters of Atoms and Molecules I, Springer Verlag
Discovery of $\text{C}_{60}$ and $\text{C}_{70}$ in a PN

Cami et al. (2010, Continuum Subtracted Spitzer Spectrum)
Dust and Radiation

**Absorption**
- Transformation of energy to some other form
- Re-emission at different wavelengths

**Incoming radiation**
- plane waves
- polarised somehow
- some spectrum

**Scattering (elastic)**
- Change in direction
- Change in polarization
- No change in wavelength
It is a difficult experimental task to produce particles a few hundred angstroms in size, keep them completely isolated from one another and all other solids, maintain them in ultra-high vacuum and at low temperatures, and study photon interactions with the particles from far infrared to extreme ultra-violet. This is the opportunity we have in the case of interstellar dust.

Donald D. Huffman
Advances in Physics, 26, 129 (1977)
Let us construct a model …

1. Assume chemical composition, shape, size, internal structure distribution

2. Select the relevant laboratory data for n, k (material structure? temperature?)

3. Calculate the cross sections (scattering codes)

4. Construct appropriate mean values

5. Apply these data in your radiative transfer calculation (or simple fitting procedure)
Basic Optical Properties of Solid Particles

The diagram illustrates the dielectric functions $\varepsilon''$ and $\varepsilon'$ in relation to the frequency spectrum. The curve labeled $\varepsilon''$ shows peaks corresponding to vibrational and electronic transitions. The debye relaxation is indicated by the $\varepsilon_{od}$ peak, and the $\varepsilon_{ov}$ peak corresponds to a vibrational transition. The frequency spectrum is divided into microwave, infrared, and ultraviolet regions.
Basic Optical Data
Cosmic Dust Analogues

• Broad Wavelength Range
• Appropriate Structure
  (Fe/Mg, am./cryst. …)
• Isolated Small Particles
• Temperature Range

MPIA Lab Astrophysics
Group at the University of Jena

Heidelberg-Jena-Petersburg database of optical constants
(Henning et al. 1999)

http://www.mpia-hd.mpg.de/HJPDOC/
Optical behaviour of small particles

After Krügel (2003) – Absorption (dots), extinction (solid line)

But: COBE Data – No single power-law emissivity law (Finkenbeiner et al. 1999)
What you need to know …
What you need to know …
• Interstellar UV bump
• Near-infrared extinction properties
• Far-infrared absorption properties
Origin of the Strong UV Resonance

- Remarkable constancy of peak position (4.60 μm⁻¹; variations smaller 1%)
- Peak width varies around mean value of 1.0 μm⁻¹ (variations smaller 25%)
- Lack of correlation between variation of peak position and width (except for the widest bumps: systematic shift to larger peak wavenumbers)
- Strength of the feature requires abundant element as part of the carrier
- Feature is pure absorption feature
What is the carrier?

- **HAC nanoparticles**
  (e.g. Schnaiter et al. 1998, Gaballah et al. 2011)

- **Large PAHs**
  (e.g. Beegle et al. 1997, Steglich et al. 2010)
Near-infrared Extinction Law

Fritz et al. 11
Optical Data of Amorphous Silicates: $\text{Mg}_x\text{Fe}_{1-x}\text{SiO}_3$

Increase of NIR absorptivity with Fe content

What are the FIR Properties of the materials?

- Structural composition of the material (e.g. Jäger et al. 1998)
- Grain size and agglomeration state (e.g. Henning & Stognienko 1996)
- Temperature of the material – to be discussed
FIR Absorption Efficiency/Spherical Particles

Jäger, Mutschke, Henning (1998)
FIR Absorption Efficiency/CDE

(see Mennella et al. 98: for low T experiments)

Jäger, Mutschke, Henning (1998)
Extinction Spectra of Carbonaceous Materials

Quinten, Kreibig, Henning, Mutschke (2002)
LOW-TEMPERATURE EFFECTS
Henning and Mutschke (1997)

Crystalline Dielectric Solids
- IR bands (single phonon transitions):
  Sharpening because of decreased damping, shift to shorter wavelengths
- FIR absorption (phonon difference processes):
  significant reduction because of decreasing phonon number

Amorphous Dielectric Solids
- FIR absorption:
  Dominated by disorder-induced single phonon processes, no temperature dependence
- Millimeter range:
  highly temperature-dependent low energy processes, e.g. tunneling transitions in glasses

Semiconductors
- free charge carrier absorption:
  vanishes because conduction band is depopulated
Explanation:

- **Lattice expansion =>** smaller forces => lower excitation frequencies
- **Moving atoms =>** broader frequency range for excitation

- **physically:** anharmonicity of potential 
  + scattering at other phonons (shorter lifetime – broader levels)

What is expected?

> Bands are broadened and shifted to lower frequencies with higher temperature
How big is the relative peak shift?

Peak pos. (10 K)
- 10.0
- 10.4
- 11.2
- 11.9
- 16.2
- 19.4
- 20.7
- 21.2
- 23.2
- 24.5
- 25.7
- 27.2
- 31.0
- 33.0
- 36.0
- 49.3
- 68.8

filled: strong
empty: middle
star: weak
cross: shoulder

forsterite

Jena
Long-wavelength forsterite bands as a thermometer

Koike et al. (2006)
Temperature Dependence – Laboratory Studies

- **Bösch (1978):** silica glass
  (500 µm – 5 mm, 1.2 – 300 K)

- **Agladze et al. (1996):** crystall. and amorphous silicates
  (700 µm – 3 mm, 1.2 – 30 K)

- **Mennella et al. (1998):** am. carbon, crystalline silicates,
  am. fayalite
  (20 µm – 2 mm, 24 – 294 K)

- **Boudet al. (2005):** am. silica, am. silicate
  (100 µm – 2 mm, 10 – 300 K)

Between 500 µm and 2 mm: Anticorrel. between T and β
\[ \beta(T, \nu) \]

- \( \Delta \) SiO\(_2\) 1.5\( \mu \)m
- \( \square \) SiO\(_2\) fumed
- \( + \) MgSiO\(_3\) sol-gel
- \( \star \) MgSiO\(_3\) glass

Break in the absorption law 
\(~30\text{cm}^{-1}:\)
Different frequency dependence

\[ \text{SiO}_2 \ \bigotimes \sim 1.5 \ \mu \text{m} \]

Anticorrelation T-\( \beta \)

\( \beta(T) \sim \text{const.} \)
Am. silicate grains with olivine composition (Mg$_x$SiO$_4$)

Experiments by K. Demyk et al.

$\beta$ changes with $\lambda$

$150 < \lambda < 700/800 \, \mu m$ : $\beta \sim 1.6 - 2.1$

$700/800 < \lambda < 1200/1300 \, \mu m$ : $\beta \sim 3.1 - 2.3$

$\beta$ increases with decrease of $T$

Mass absorption coefficient (MAC) decreases with decrease of $T$
Which new dust features can we expect to see with Herschel?

FIR: Lattice vibrations of heavy ions or ion groups with low bond energies (example KBr: transverse optical mode at 86 µm); PACS: 57-210 µm

- Forsterite 69 µm band
- Fayalite 93-94 µm and 110 µm band
- Crystalline Diopside 65-66 µm
- Hydrous silicates 100-110 µm (e.g. montmorillonite)
- Calcite CaCO₃ 92 µm
Herschel – Predictions and PACS Spectra

HD 100546, DIGIT Program
Sturm, Bouwman, Henning et al. (2010)

Measured position is 69.2 µm
(Cold (50 K) iron-free forsterite has a peak at 69.0 µm)

a) Warm iron-free grains create the shift (150-200 K)
(Mulders et al. 2011)

b) Cold forsterite with a few percent iron shifts feature
FIR optical data of interesting materials

Carbonates, silicates, hydrous silicates at low temperatures

- **Hydrous silicates:** Mutschke et al. (2008)
- **Carbonates:** Posch et al. (2007)
- **Olivine:** Bowey et al. (2001), Suto et al. (2006), Koike et al. (2006)
- **Diopside:** Bowey et al. (2001), Chihara et al. (2001)

![Jena data](image-url)

CaMg[Si$_2$O$_6$]
Towards a Dusty Universe ….  

- Basic understanding of grain properties  
- Formation and evolution of grains - next challenge
Absorption, scattering, and emission by interstellar material produces enough puzzles, even of identification, to keep the proverbial seven spectroscopists with seven brooms busy for at least seven years.

Trimble & Aschwaden (1998)

“Sure it’s beautiful, but I can’t help thinking about all that interstellar dust out there.”