The Dusty Universe: From ISO and Spitzer to Herschel, SOFIA, and JWST

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Key Questions

- Where: Origin of Interstellar dust
- What: Inventory of interstellar dust
- How: Key processes in its formation and evolution
- When: Interstellar dust over the ages
- Why: Do we care
Spitzer Survey of the Large Magellanic Cloud: Surveying the Agents of a Galaxy’s Evolution (SAGE), PI: Meixner

http://sage.stsci.edu/

IRAC 3.6 µm
IRAC 8.0 µm
MIPS 24 µm

Gordon & SAGE team
(Meixner et al. 2006)
Inventory of the LMC

AGB stars: Blum et al. (2006)
YSO candidates: Whitney et al. (2008)
PNe: Hora et al. (2008)
Empty field = background galaxies: Whitney, Sewilo et al. (2008)

Final Source Counts:
~6.3 million point sources
>650,000 red giant stars
>45,000 dusty evolved stars
>1200 Young Stellar Objects
AGB Dust Mass Loss Return

First cut based on colors

Contributions

- \(10^{-5} \, M_\odot \, \text{yr}^{-1}\)
- 0.14 (O-rich)
- 0.24 (C-rich)
- 2.36 (Extreme)
- 2.74 (All)

Srinivasan et al. 2009
SAGE-Spec: LMC
PI: F. Kemper

First analysis based on spectroscopy: to be completed
# SAGE-LMC Inventory

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass or rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass of dark halo</td>
<td>$\sim 1 - 3 \times 10^{10} , M_\odot$</td>
</tr>
<tr>
<td>Stellar Mass</td>
<td>$3 \times 10^9 , M_\odot$</td>
</tr>
<tr>
<td>ISM mass, 160 $\mu$m</td>
<td>$10^9 , M_\odot$</td>
</tr>
<tr>
<td>Star formation rate</td>
<td>$\sim 0.1 , M_\odot , yr^{-1}$</td>
</tr>
<tr>
<td>AGB Mass Loss return</td>
<td>$6 - 13 \times 10^{-3} , M_\odot , yr^{-1}$</td>
</tr>
<tr>
<td>Planetary nebulae Massive stars: Red supergiants, LBV, SNs</td>
<td>$\sim 3 \times 10^{-2} , M_\odot , yr^{-1}$</td>
</tr>
</tbody>
</table>
Spitzer & Supernova

- SN ejecta
  - limited to the near universe (~10Mpc)
  - inefficient dust formation
- Young SNRs
  - biased to warm (shocked) dust
  - Silicates, oxides & PAH (clusters)

Also Akari, see Seok p43
Herschel & Supernova

- **Young SNRs**
  - Warm dust in reverse shock region
  - Cool dust interior to reverse shock region
  - $M_{\text{dust}} \approx 0.075 \, M_{\odot}$

Barlow et al., 2010, A&A, 518, L138
The Spectral Richness of Dust
Dust Inventory of the ISM

- Silicates:
  - Amorphous FeMg-silicates
  - Forsterite
  - Enstatite
  - Montmorillonite ?

- Oxides:
  - Corundum
  - Spinel
  - Wuestite
  - Hibonite
  - Rutile

- Sulfides:
  - Magnesium sulfide
  - Iron sulfide ?

- Ices
  - Simple molecules such as $H_2O$, $CH_3OH$, $CO$, $CO_2$

- Carbides:
  - Silicon carbide
  - Titanium carbide
  - And others

- “Pure” Carbonaceous compounds:
  - Graphite
  - Diamonds
  - Hydrogenated Amorphous Carbon
  - Polycyclic Aromatic Hydrocarbons
  - Fullerenes

- Others:
  - Silicon nitride
  - Metallic iron ??
  - Carbonates ?
  - Silicon/silicon dioxide ??
• Oxides at low mass loss rates
• Silicates at high mass loss rates
• Freeze out

Cami, 2001, PhD thesis
Spitzer’s Contribution

- Systematic studies
- Metallicity dependence with LMC, globular cluster & bulge samples
  - more metals = more dust
  - diversity is everywhere
  - composition not dependent on metallicity
- Larger samples are needed

Sage-spec
Blommaert et al, in prep
Crystalline Silicates Galore

ISO

- Crystalline silicates
  - Forsterite/enstatite
  - Magnesium-rich
  - Cold
  - Disk sources
- Amorphous silicates
  - Role of iron
- High mass loss rates

Molster et al., 2000, A&A 382, 184
Crovisier et al, 1997, Science, 275, 1904
Crystallinity and Grain Growth

Van Boekel et al., 2005, AA, 437, 189
Spitzer’s Contribution

• Large systematic samples
• Disks are everywhere: differences & similarities
  - Herbig Ae & Be stars (ISO)
  - T Tauri stars
  - Brown Dwarf disks
• Better characterization of dust composition
  - eg., silica

The 69 µm Forsterite Band

ISO
Width and peak position are sensitive to composition & temperature

Laboratory-Observations
- Composition: Mg$_2$SiO$_4$
- Temperature: <200 K

See also Brusentsova, PI

Herschel’s Contribution

Accurate profiles & detailed models

- ‘perfect’ crystals
- ‘pure’ forsterite (<few % Fe)
- temperature gradient

Dust Formation in IRC+10216

Herschel & the power of spectroscopy
## First PACS +SPIRE Spectroscopic Results

### Molecular inventory

**VY CMa**
- $^{12}$CO, $^{13}$CO, $^{17}$O, $^{18}$O
- NH$_3$
- OH
- SiO
- HCN
- CN
- CS
- SO
- SiS
- $\text{H}_3\text{O}^+$?
- [C II]
- [O I]

{2/3 of all lines}

**TOTAL: ~500 unblended**

**IRC+10216**
- $\text{H}^{12}\text{CN}$
- $\text{H}^{13}\text{CN}$
- $^{12}$CO, $^{13}$CO, $^{18}$O
- o-H$_2$O
- p-H$_2$O
- NH$_3$
- SiS
- SiO
- CS
- HCl

{1/2 of all lines}

**TOTAL: ~500 unblended**

+ unidentified lines
Silicon in the Dust Formation Zone

High $J$ lines of SiO and SiS: Trace dust formation zone

SiO: $J = 11-10$ to $J = 90-89$ ($E_{up} = 8432$ K)
SiS: $J = 26-25$ to $J = 124-123$ ($E_{up} = 6678$ K)
Silicon in the Dust Formation Zone

Less than 30% of the silicon seems involved
HIFI & Dust Acceleration

Herschel will probe the gas-to-grain process

The incredibly rich spectrum of interstellar PAHs

PAH Spectral Variations

ISO

- Profile variations
- Strongest for CC modes
- Classes A, B, C
- Classes correlate well for CC modes
- Correspond to object type

PAHs in Regions of Star Formation

Spitzer

- Variations in the peak position of the 7.7 μm band
  - Aromatic versus aliphatic hydrocarbons
  - N incorporation into rings or clusters
- Active chemistry

PAHs and Herbig Stars

<table>
<thead>
<tr>
<th>Source</th>
<th>Sp T</th>
<th>Size</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>TY Cra</td>
<td>B7-B9</td>
<td>~2000 AU</td>
<td>HAeBe in cloud</td>
</tr>
<tr>
<td>HD 97048</td>
<td>B9-A0</td>
<td>~100-1000 AU</td>
<td>HAeBe cloud edge</td>
</tr>
<tr>
<td>HD 100546</td>
<td>B9</td>
<td>~150 AU</td>
<td>isolated HAeBe star</td>
</tr>
</tbody>
</table>

IR emission spectra are very similar, particular in the "extreme" regions of the ISM.

- 15-20 micron region dominated by a few bands (16.4/17.4/17.0 micron)
- Typical PAH will absorb some $10^8$ UV photons over its lifetime. What can break, will break.
- Interstellar PAH family dominated by a few, extremely stable species.

\[ C_{96}H_{24} \]
Fullerenes in Space

Buckyballs In A Young Planetary Nebula

Spitzer Space Telescope • IRS

See Cami et al, P2

C_{60}  C_{70}

NASA / JPL-Caltech / J. Cami (Univ. of Western Ontario/SETI Institute)
PAHs dominate the spectra but C60 is present as well at 0.3% of the C

PAH & Fullerene Chemistry

- Stellar ejecta
  - Fullerenes at \(\sim 3500\) K
  - PAHs at \(\sim 1000\) K
- H-poor environments
  - RCrB stars, WC stars
  - vaporizing grain-grain collisions
- UV photochemistry
  - H-loss
  - isomerization

Herschel may probe the ‘grandPAH’ evolution
Key Questions

- Where: Origin of Interstellar dust
- What: Inventory of interstellar dust
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Key Questions:
ISO & Spitzer Answers

• What: The rich inventory of interstellar dust
• Where: AGB stars (and elsewhere including ISM)
• How: Dust condensation sequence
• When: To be done
• Why: planetary formation & molecular complexity
Key Questions: Herschel’s promise

- **What:** Cold dust in the ISM
- **Where:** will add supernova remnants
- **How:** Gas-Grain interaction in AGB ejecta
- **When:** To be done
- **Why:** planetary formation & molecular complexity
Dust Inventory: what & where

**SOFIA:**
- census of stardust injected into the Milky Way
- compare to interstellar dust characteristics
- Volume limited sample of stardust sources in the Milky Way based on GAIA distances

**JWST/MIRI:**
- census of stardust injected into the Andromeda Galaxy
- Contribution from cannibalized dwarf galaxies
- Dust formation in supernova ejecta
Dust & Gas: How

SOFIA

- Wide spectral coverage & high spectral resolution
- Dust formation & destruction
- Molecular complexity
- Continue where Herschel will leave off
PAHs & Dust Evolution in Protoplanetary Environments

JWST

- Silicates: composition, crystalization and grain growth in the terrestrial zone
- PAHs: Organic inventory & tracing the geometry of the disk
Dust through the Ages

JWST

Dust composition in extreme environments: quasar (winds), ULIRGS, super star clusters, SNe, high-z

From ISO to Spitzer to Herschel to SOFIA to JWST, the dusty revolution continues