Interstellar Dust and PAHs

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Interstellar Dust

Role of dust:

- Dominant opacity source FUV-submm
- Dominates spectral appearance of galaxies
- Reservoir of elements
- Dust & molecules
  - Limits molecular photodissociation
  - Catalytic surfaces
  - Cold storage
- Photo-electric heating and the energy balance of the gas
- Cosmic Rays
- Building blocks of planetary systems
Tielens Ancestry
The Lifecycle of Baryonic Matter

low mass stars high mass stars

credit: http://hea-www.cfa.harvard.edu/CHAMP/EDUCATION/PUBLIC/ICONS/
Cosmic Journey of Interstellar Dust

Stellar evolution
nucleosynthesis

Stellar death
Dust formation:
Chemical nucleation,
growth, agglomeration

Star formation
Nebular processing,
Jet processing
X-ray processing

Cloud phase
Chemical mantle growth
Thermal processing

Intercloud medium
Dust destruction:
Shock sputtering
Processing by UV, X-rays, & cosmic rays

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Key Questions

• What is the inventory of interstellar dust?
• What are the important sources of dust and how does that depend on metallicity and star formation rate of the galaxy?
• What processes played a role in the evolution of dust in the interstellar medium?
• What kind of dust entered the Solar Nebula?
• What processes played a role in the evolution of dust in the planetary systems?
• How did dust evolve with time in the Universe?
• How is dust affected near black holes and in starburst environments?
• How did the evolution of dust affect the evolution of galaxies, stars and planets?
Probing the Dust: 1 Dust Inventory
The Spectral Richness of Dust

- ISO and Spitzer have revealed the incredible spectral richness of interstellar dust
- JWST will carry this to the era of vigorous star formation in the Universe
- SPICA will probe the high-z Universe
- Herschel will probe the far-IR
- SOFIA can probe bright stardust sources in the Milky Way to link these spectral characteristics to the characteristics of the stardust sources and turn this into a tool for understanding the origin of dust in the Universe

Hony, 2001, PhD thesis
Dust Inventory of the ISM

- **Silicates:**
  - Amorphous FeMg-silicates
  - Forsterite
  - Enstatite
  - Montmorillonite
- **Oxides:**
  - Corundum
  - Spinel
  - Wuestite
  - Hibonite
  - Rutile
  - Silica
- **“Pure” Carbonaceous compounds:**
  - Graphite
  - Diamonds
  - Hydrogenated Amorphous Carbon
  - Polycyclic Aromatic Hydrocarbons
- **Carbides:**
  - Silicon carbide
  - Titanium carbide
  - And others
- **Sulfides:**
  - Magnesium sulfide
  - Iron sulfide
- **Ices:**
  - Simple molecules such as H$_2$O, CH$_3$OH, CO, CO$_2$
- **Others:**
  - Silicon nitride
  - Metallic iron
  - Carbonates
Sources of Stardust

- Spitzer: Origin of dust in the low metallicity Magellanic Clouds (SAGE & SAGE-Spec)
AGB Stars & the ISM in the LMC

Dust mass injection into the ISM:
~23,000 AGB stars & 2.7x10^{-5} M_{\odot}/yr

Extreme AGB ~2.4x10^{-5} M_{\odot}/yr
O-rich AGB ~1.4x10^{-6} M_{\odot}/yr
C-rich AGB ~2.4x10^{-6} M_{\odot}/yr


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• SOFIA can provide a full census of stardust injected into the Milky Way and compare it to interstellar dust characteristics

• JWST can uniquely probe punctuated evolution: contributions from e.g., captured dwarf galaxies

• JWST can probe IR dust extinction

• Volume limited sample of stardust sources in the Milky Way based on GAIA (2012-2020) distances
Cosmic Journey of Dust: 
2 Dust Formation
Thermodynamic Condensation Sequence

- Gas with solar system composition
- Condensation is sequential
- Two major sequences
  - Oxides: starting with aluminum oxide/spinel and ending with Ca,Al silicates
  - Silicates: starting with forsterite and forming enstatite
- Separate sequence for C-rich gas characterized by carbonaceous compounds

Salpeter, 1977, ARAA, 15, 267
Oxides Condensation Sequence

- Oxides at low mass loss rates
- Freeze out


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The Incredibly Rich mid-IR Spectrum of Crystalline Silicates

Characteristics

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


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The 69 \( \mu \text{m} \) band

Crystalline band characteristics:

Peak position and width depend on the composition and temperature of the material

Mg-rich end members of the olivine and pyroxene families (Fe/Mg<5%): Forsterite and enstatite

\( T \sim 100-200 \text{K} \)


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AGBs as Dust Condensation Laboratory

- Two condensation sequences:
  - Oxides
  - Silicates
- Time is of the essence
- AGBs are templates for SNe and other dust factories
- Controlled stellar samples are required

Tielens, 2010,
The First Clusters

- What is the structure of the first molecular clusters?
- How does their formation depend on environment?
- How does that influence the dust formation process?

Dust in Extreme Environments

SOFIA can probe stellar dust laboratories and relate the dust characteristics to the environment.


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Cosmic Journey of Dust: 3 Processing in the ISM
Dust & Interstellar Shocks

- Supernovae eject material at ~10,000 km/s
- This high velocity gas drives a strong shock wave, sweeping up interstellar material
- As the supernova remnant expands, the shock velocity will decrease until the swept up gas (and ejecta) merge with the interstellar medium
- Shocks destroy dust grains through sputtering and shattering
- 100 km/s shock “chips” 30 Å layer from a 1000Å grain
- Calculated lifetime: ~500 Myr

Shocks, Depletion & Grain Growth

- Depletion: elements are locked up in dust
- High velocity gas has less depletion
- Intercloud gas has less depletion than cloud gas
- Interstellar shocks in the intercloud medium sputter a thin outer layer (~30Å) which is rapidly reaccreted in diffuse clouds
- Carbon is not involved in these mantles
- Carbonaceous mantles from energetic processing of ices in molecular clouds or Solar nebula ??

Grain Growth

- Dust life time $\ll$ injection time scale
- Grain growth is important
- Dust loses and reacquires thin veneer or is it ‘completely’ reformed?
- Is interstellar dust dominated by stardust or by “mantled” dust?

SOFIA can probe the relationship between stardust and interstellar dust.
4 Interstellar PAHs
The incredibly rich spectrum of interstellar PAHs
PAH Band Variations

- C-H and C-C modes vary independently

Blind Signal Separation & Principal Component Analysis methods

The Spectral Characteristics of PAHs

PAH spectra depend on:

- charge state
- size
- molecular structure
- clustering
- complexing
- heteroatoms
- temperature
- .....
Emission Components

- PAHs (IR features)
- Clusters (plateaus)
- Very Small Grains (mid-IR Cirrus)
- Big Grains (far-IR continuum)

Models differ in the components and characteristics adopted
The Relationship of PAHs & Dust

• PAHs are the extension of the interstellar grain size distribution into the molecular domain
• PAH/VSG/Dust grain abundance ratios vary with physical conditions/history
SOFIA can relate observed variations to local physical and chemical processes
PAH Ionization Balance

- Ratio of C-H/C-C modes measures charge state
- Calibrate PAH band ratios on well-studied PDRs
- Diagnostic atomic and molecular ‘PDR’ lines
- SOFIA can link the observed spectral characteristics of PAHs to the local physical and chemical characteristics


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The ISM is a Harsh Mistress

Lifecycle of Interstellar PAHs

Timescales estimated by extrapolating solid state concepts into the molecular domain

- Formation C-rich AGB stars
- Shocks/Cosmic Rays
  - Lifetime ~ 100 Myr
- UV lifetime 100 Myr
- Reaction rates are poorly known for large PAHs
- AGB star injection timescale ~ 2 Byr


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Origin of Interstellar PAHs

- PAH life time << injection time scale
- Are interstellar PAHs dominated by starPAHs or by interstellar PAHs?
- PAHs as the leftover condensation nuclei in the soot formation route in stellar ejecta
- PAHs as the fragmentation products in grain-grain collisions in interstellar shocks

PAH Spectral Variations

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

- Peak position of the 7.7 μm band varies depending on source type
- Active chemistry

PAHs and Herbig Stars

Chemical Modification of PAHs

Origin of peak shifts

- N in the carbon skeleton
- PAH clusters (with Fe)
- PAH clusters
- Aliphatic/aromatic carbon variations

MIRI/JWST will be able to probe the spectral & chemical evolution of PAHs in regions of star and planet formation

- Chemical inventory
- Chemical processes:
  - UV/ X-ray/thermal
- Physical processes:
  - mixing/lightning/shocks
SOFIA – by probing a wide range of environments – can link observed spectral variations to the physical and chemical processes
GrandPAHs

- IR emission spectra are very similar, particular in the “extreme” regions of the ISM

- 15-20 µm region often dominated by a few bands (16.4/17.4/17.0 µm)

- Typical PAH will absorb some 100 Million UV photons over its lifetime what can break, will break

- Interstellar PAH family dominated by a few, extremely stable species
SEARCHING FOR THE ‘GRANDPAH’

- The far-IR ‘drum beat’ modes are highly molecule specific

- Only SOFIA can measure all vibrational modes of interstellar PAHs

- Sample of objects with different conditions and different PAH family to probe chemical evolution and key processes
Identification of specific PAHs

- Drumhead modes: Lowest-lying vibrational state will emit when the modes have decoupled

- Observing strategy: search for Q-branch at moderate resolution over full spectral range

- Follow up with high resolution search for P/R branches

- SOFIA (& Herschel) can search for these signatures of the grandPAHs

Summary

– Infrared missions have provided us with an unprecedented view of the dusty & molecular Universe
– Most of the heavy elements are injected as “stardust” into the interstellar medium
– Space is a harsh mistress: Dust & PAHs are heavily processed in the ISM
– Undoubtedly, dust has strongly evolved over the lifetime of the universe as stellar populations change, star formation activity varies, and punctuated energetic events take their toll
PAHs & Dust in the Universe

- What are the characteristics of dust & PAHs injected by different stellar sources?
- What is the contribution of low mass versus massive stars to the ISM budget?
- How does this depend on metallicity and other galaxy characteristics?
- How does this compare to the local interstellar dust characteristics?
- What processes control the evolution of dust & PAHs in galaxies?
- What does this imply for dust & PAHs in extreme environments?
PAHs & Dust in the Universe

SOFIA’s Niche:

• Mass inventory of stardust sources in the local Milky Way & comparison to interstellar dust

• Dust formation characteristics in stellar environments

• PAH characteristics and their relationship to the physics and chemistry of the environment

Building upon ISO & Spitzer and with contributions from Gaia, ALMA, & JWST

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New Instrumentation

- Moderate resolution ($R=300-1000$) spectrometers covering from 3 to 300 microns
- Integral Field spectrometers ($R=300-1000$) in the mid-IR (3-20 micron)
- plus
  - High resolution spectrographs to probe the physics of the medium