Hot Dust and Molecular Gas in Interacting Galaxies:

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Topics / Questions

- Why should we care about dust?
  - How can we use dust to study the energy balance in galaxies?
- Why study interacting galaxies and their dust content?
  - How does dust affect their morphology or even detection?
- What have we learned from the Infrared Space Observatory?
- How is dust related to the molecular gas, the fuel of activity?
  - How well is the star formation rate/activity determined?
- What does the (not so distant) future hold?
Dust - Importance

◆ Dust is everywhere!
  – Wavelength dependent extinction
  ◆ Broad bump at 217.5 nm (carbonaceous material, graphite)
  ◆ Diffuse Interstellar Bands at few ~ 100s nm
  ◆ Presence of absorption features attributed to ice (3.1 µm)
  ◆ IR features at 9.7 & 18 µm (amorphous silicates ~ olivine \( \text{Mg}_x\text{Fe}_{2-x}\text{SiO}_4 \))
  – Polarization of starlight
  – X-ray halos around X-ray point sources
  – Infrared emission from dust grains + aromatic hydrocarbons
  – Meteorites (carbonaceous chondrite)
  – Impacts on space probes!

(Draine 1999)
Dust – Importance (2)

◆ Directly coupled to Star Formation
  – *Forms at late stages of stellar evolution*
  – *Acts as catalyst for the formation of molecules*

◆ Dust grains scatter and absorb light → **selective** extinction of radiation

Galactic center $A_V \sim 30$ mag → 1 photon in $10^{12}$ penetrates

$A_{2.2 \, \mu m} \sim 2.5$ mag → 1 photon in 10 penetrates

◆ Dynamics of Interstellar Grains
  – *Gas drag (direct collision + momentum transfer with atoms & ions)*
  – *Radiation pressure + grain destruction*
  – *E&M forces on charged grains (polarization)*
  – *Recoil due to photoelectric emission, $H_2$ formation*
  – *Gravity – grains go to the minimum of a gravitational potential*
Dust – types

Dust grains range in size from a few hundred Å to a few µm. They are composed mainly of elements such as carbon and silicate compounds, and various kinds of ices.

“classical” dust grains \( \rightarrow 0.1 \ \mu m \) in size, containing \( \geq 10000 \) atoms responsible for the FIR, sub-mm emission

very small grains \( \rightarrow \) containing \( \leq 100 \) atoms (less than 10nm in size) responsible for a rising continuum \( \sim 10 \mu m \)

PAHs (Polycyclic Aromatic Hydrocarbons) \( \rightarrow \) benzene rings contain \( N \sim 50 \) atoms trace photodissociation regions.

Due to the size distribution & variations in the underlying radiation field the dust temperature varies (cold, warm, hot dust)

Spectra of different dust components are fitted by modified Planck curves

\[ I_\nu \propto \varepsilon_\nu \ B_\nu(T) \]

Power-law emissivity: \( \varepsilon_\nu \propto \nu^n \)

Really hot dust (~200-1500K) in a equilibrium is observed via a near/mid-IR “bump” close to tori of AGNs.
Experimental Data for PAHs

**PAH infrared features**

- C-H stretch (3.3 µm)
- C-C stretch (6.2, 7.7 µm)
- C-H in plane bend (8.6 µm)
- C-H out of plane bend (11.3, 11.9, 12.7 µm)
- C-C bending (16.4, 18.3, 21.2, 23.1 µm)

*Fig. 1.* — Comparison of (a) the infrared emission spectrum of the Orion bar with (b) a composite absorption spectrum generated by co-adding the individual spectra of 11 PAH cations. The individual spectra were calculated using experimentally measured frequencies and intensities and assigning a 30 cm\(^{-1}\) FWHH Gaussian band profile, consistent with that expected from the interstellar emitters (Allamandola et al. 1989). The PAH cation mixture consists of 20% benzo[k]fluoranthene\(^+\) (C\(_{22}\)H\(_{16}\)) and dicrotonylene\(^+\) (C\(_{14}\)H\(_{10}\)); 10% coronene\(^+\) (C\(_{20}\)H\(_{12}\)), benzo[b]fluoranthene\(^+\) (C\(_{20}\)H\(_{12}\)), 9, 10-dihydrobenzo(e)pyrene\(^+\) (C\(_{20}\)H\(_{16}\)), and phenanthrene\(^+\) (C\(_{16}\)H\(_{10}\)); 5% benzo[ghi]perylene\(^+\) (C\(_{22}\)H\(_{14}\)); tetracene\(^+\), and benzo[a]anthracene\(^+\) (both C\(_{18}\)H\(_{12}\)); and 2% chrysene\(^+\) (C\(_{18}\)H\(_{12}\)) and fluoranthene (C\(_{12}\)H\(_{10}\)). The Orion spectrum is reproduced from Bregman et al. (1989).

Theoretical Modeling of PAHs

Stochastic Heating of grains

◆ A far-UV photon hits a dust grain and ejects an electron

◆ The ejected photoelectron heats the gas (very inefficiently ~0.1 - 1 %)
  – 50% of gas heating is due to grains of sizes < 15 Å

◆ Subsequently the gas cools via far-IR emission lines ([OI] 63 µm, [CII] 158 µm)

◆ Process of randomly heating dust grains to high T (~1000K) for short periods (~1s)
  – Not in equilibrium.

◆ PAHs, dominate the mid-IR (5-20 µm) flux in normal galaxies and quiescent star forming regions via the so-called Unidentified IR Bands (UIBs) or IR Emission Features (IEFs).

◆ In normal late type galaxies most of their energy is released in the FIR.
Energy Balance

\[
\log \frac{[\mathrm{CII}]}{\nu^2} (5-10 \mu \text{m})
\]

\[
\sigma = 0.18 \ \text{dex}
\]

\[
\log \frac{[\mathrm{CII}]}{\nu B} (5-10 \mu \text{m})
\]

\[
\sigma = 0.37 \ \text{dex}
\]

\[
\log f_\nu(60 \mu \text{m}) / f_\nu(100 \mu \text{m})
\]

Why study Interacting Galaxies?

- **Most galaxies are not isolated** (Baade 1920)
- Interactions determine the morphology and evolution of galaxies.
- Our own Galaxy is interacting with the LMC and SMC
- The galaxy merging rate increases with redshift $\sim (1+z)^m$, $m>2$ (Lavery et al. '96)
  
  => Cosmological implications (always helps to attract attention!)

- **Massive starbursts are found in regions with high dust content**
  - *they are hidden in the optical* -> IRAS (Soifer et al. 1984, Houck et al. 1984)
  - *most of the energy is emitted in the infrared wavelengths*

- **Nearly all Luminous IR galaxies** (LIGs) are mergers (ie. Sanders 1988)
- The optical/near-IR morphology is misleading (Mirabel et al. 1998)
A Veil of Dust

The SED of LIGs

In the Mid-IR:

• we are less affected by absorption than in optical $A_V = 70 * A$ (15 $\mu$m)
• better spatial resolution than Far-IR

BUT…

• Only a fraction of the bolometric luminosity is emitted in the mid-IR.

Can we still say something about the global energy production using the mid-IR?

YES!

Typical mid-IR spectrum with ISO

- Band emission from Polycyclic Aromatic Hydrocarbons (PAHs or UIB)
- Continuum emission attributed to Very Small Grains
- Ionic/high excitation line emission
PDR-like regions in the mid-IR
HII-like regions in the mid-IR
AGNs in the mid-IR
The MIR spectrum varies
Toomre’s Merging Sequence

A sample of galaxies where we know a priori their stage of interaction

<table>
<thead>
<tr>
<th>Source</th>
<th>LW2 (5-8.5 μm) (mJy)</th>
<th>LW4 (5.5-6.5 μm) (mJy)</th>
<th>LW3 (12-18 μm) (mJy)</th>
<th>LW2 LW4</th>
<th>LW3 LW2</th>
<th>log(10 RAS(60μm)/10 RAS(100μm))</th>
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</thead>
<tbody>
<tr>
<td>NGC 4676(B)†</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>–</td>
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<tr>
<td>NGC 4676(A)†</td>
<td>58</td>
<td>40</td>
<td>30</td>
<td>1.45</td>
<td>0.52</td>
<td>-0.28</td>
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<tr>
<td>NGC 3263 (Nuc : 4.5’’)</td>
<td>59</td>
<td>31</td>
<td>61</td>
<td>1.90</td>
<td>1.03</td>
<td>-0.42</td>
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<tr>
<td>NGC 520</td>
<td>485</td>
<td>231</td>
<td>522</td>
<td>2.10</td>
<td>1.08</td>
<td>-0.16</td>
</tr>
<tr>
<td>NGC 3256 (Nuc : 4.5’’)</td>
<td>441</td>
<td>211</td>
<td>1195</td>
<td>2.09</td>
<td>2.71</td>
<td>-0.12</td>
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<tr>
<td>NGC 3256 (Disk)</td>
<td>201</td>
<td>84</td>
<td>426</td>
<td>2.10</td>
<td>2.12</td>
<td>–</td>
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<tr>
<td>NGC 6240</td>
<td>212</td>
<td>100</td>
<td>785</td>
<td>2.12</td>
<td>3.70</td>
<td>-0.09</td>
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<tr>
<td>Arp 220</td>
<td>141</td>
<td>60</td>
<td>714</td>
<td>2.35</td>
<td>5.06</td>
<td>-0.04</td>
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<td>NGC 7252</td>
<td>70</td>
<td>28</td>
<td>100</td>
<td>2.50</td>
<td>1.42</td>
<td>-0.25</td>
</tr>
<tr>
<td>NGC 3921</td>
<td>35</td>
<td>–</td>
<td>42</td>
<td>–</td>
<td>0.82</td>
<td>-0.38</td>
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<tr>
<td>NGC 4038/39 (KnotA : 6’’)</td>
<td>82</td>
<td>41</td>
<td>399</td>
<td>2.00</td>
<td>4.87</td>
<td></td>
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<tr>
<td>NGC 4038/39 (Nuc : 6’’)</td>
<td>55</td>
<td>23</td>
<td>115</td>
<td>2.39</td>
<td>2.10</td>
<td></td>
</tr>
</tbody>
</table>
Early stage interactions – pre-starburst phase

1. NGC 4676
   - DSS image
   - 7 μm image
   - Mid-IR SED

2. NGC 3263
   - DSS image
   - 7 μm image
   - Mid-IR SED

3. NGC 520
   - DSS image
   - 7 μm image
   - Mid-IR SED

4. NGC 3256
   - DSS image
   - 7 μm image
   - Mid-IR SED

Mergers/Merger remnants – post-starburst phase

5. NGC 6240

6. Arp 220

7. NGC 7252

8. NGC 3921

DSS image  7 μm image  Mid-IR SED
Mid-IR Far-IR Correlation

ISO: 15µm / 7µm

IRAS 25µm / IRAS 12µm

IRAS 60µm / IRAS 100µm

Mid-IR imaging does reveal the intensity/age of a starburst
How does absorption affect the form of the Mid-IR SED?

- Arp 220
- H₂ (S5)
- 6.2, 7.7, 8.6, 11.3
- Silicate absorption

- NGC 6240
- H₂ (S5), H₂ (S3)
- 6.2, 7.7, 8.6, 11.3
- Silicate absorption
We can estimate a “de-reddened” spectrum by fitting a black body after taking into account the shape of the extinction curve and the contribution of the UIB lines.

Absorption effects in AGNs...

The case of N1068 (Sy2):

Hiding the central region (3''x3'') behind an increasingly dense screen of dust…
… the galaxy becomes starburst-like

ISO conclusions:

- The LW3(15µm) / LW2(7µm) mid-IR flux indicator is a powerful diagnostic of the star formation intensity.
- The 15µm / 7µm ratio is correlated with the IRAS colors suggesting that the mid-IR spectrum may be used as a tracer of the far-IR SED.
- None of the galaxies presented shows AGN characteristics However…
- …the absorption in merger remnants is high (ie Arp220, NGC6240) so a based only on mid-IR data a weak enshrouded AGN can not be excluded

Problems:
- Measuring the extinction using only the 5-17 µm range is “tricky”.
- If one uses a mixed instead of a screen model for dust the estimated Av increases (factor 4-5).
- If all galaxies host a black hole its contribution in mid-IR needs to be quantified
- ISO integrated spectra over large areas. Smaller slit sizes are necessary.
The Role of the Molecular Gas in IAGs

- Most star formation (SF) takes place in Giant Molecular Clouds (GMCs)
  - The distribution of GSMs is different than the HI gas (Milky Way)
  - Limitations in mm arrays hinder detailed observations/analysis in other galaxies
  - Few well studied examples of interacting systems (ie. NGC4038/39)

- Globally the high mass SF is estimated by the FIR luminosity (insensitive to Av)
- Typically the molecular gas is traced via CO(1-0) emission (n ~>300cm⁻³)
- The Star Formation Efficiency is measured by \( \frac{L_{\text{FIR}}}{L_{\text{CO}}} \) or \( \frac{L_{\text{FIR}}}{M_{\text{VT}}} \)

- Problems:
  - Make sure we observe / take into account all molecular gas
  - Metallicity gradients/changes add a fudge factor in converting CO to \( H_2 \) mass
  - \( M_{\text{VT}} \) estimates are not always robust as one needs to measure both GMC sizes and CO line widths assuming that the clouds are virialized.
Global CO/FIR correlations

- Normal/weakly interacting galaxies behave similarly to galactic GMCs.
- Luminous IR galaxies deviate.

**Why?**

- Not all molecular gas is associated with the on-going star formation activity.
- In extreme starbursts only the denser gas in the central regions "counts".

- The HCN(1-0) has short lifetime and traces denser gas \((n > 30,000\text{cm}^{-3})\)
- A better tracer of massive SF in starburst luminous IR galaxies.
- Potential use for detection of AGN contribution to LIR via a scatter in the FIR/HCN
**Total:**  $M_{\text{CO}} = 5.3 \times 10^9 \ M_{\text{SUN}}$

- 2.2x more than Stanford et al, 1990
- same to single dish by Sanders et al, 1985

**Mass of GMCs = 3-6 \times 10^9 \ M_{\text{SUN}}**

Evidence of collision between GMCs -> explain the spectrum of the mid-IR peak.

NGC4038/39 – Revisited (2)

**CO(1-0)**

**HCN**
Lessons learned from the recent work on NGC4038/39

- Most of the molecular gas was unaccounted up to now.
- Its distributions/kinematics agree with the mid-IR picture of the galaxy.
- The SFE is low ($4.2 \, L_{\odot}/M_{\odot}$) globally, increasing by a 5x near the mid-IR peak.
- The galaxy has not yet to reach its peaks of SF activity.
- Its HCN content is 3 times less than typical star forming galaxies. Why?
CenA - another tough case...

A barred spiral inside CenA
Does all gas go into the center?

- **Evidence:**
  - HI gas at outskirts of Es/S0s
  - ~50% of Es/S0s have stellar shells indicating accretion of small companion(s)
  - If gas dissipates fast how does it reach those regions?
  - What happens with the cold molecular phase of ISM?

• 50% of the gas in the shells of CenA is in molecular phase
• More than 10% of the molecular gas in CenA is away from the nucleus
• Could molecular gas contribute to the dark matter in galaxies? (ALMA)
• Why?
• The clumpy cold molecular gas has low dissipation -> behaves as stars do!
The combination of mm and IR observations is imperative.

Sensitivity and spatial resolution is the name of the game…

In the infrared SIRTF and IRS (my sponsor) will identify spectral features of sources which up to now were not sufficiently bright to image.

In the mm wavelengths ALMA will revolutionize the study of the molecular gas and its dynamics with subarcsec resolution the same way VLA did of HI 20 years ago.

Answers to many questions remain “obscured”, so all young at heart live in an exciting time of (extragalactic) astronomy.

“If we are not prepared for the unexpected we’ll never discover it”
– Heraclitus (~500BC)