Dust and mid-IR properties of Interacting Galaxies and AGN

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Yale University – September 12th 2002
Dust - Importance

◆ Dust is everywhere!
  – *Directly coupled to Star Formation*
    Forms at late stages of stellar evolution
    Acts as catalyst for the formation of molecules
  – *Wavelength dependent extinction*
    Galactic center:  \( A_V \sim 30 \text{ mag} \)  \( \rightarrow \) 1 photon in \( 10^{12} \) penetrates
    \( A_{2.2 \mu m} \sim 2.5 \text{ mag} \)  \( \rightarrow \) 1 photon in 10 penetrates
  – *Continuum bump at \( \sim 100 \mu m \)*
  – *Presence of ice absorption features (3.1 \( \mu m \))*
  – *IR features at 9.7 & 18 \( \mu m \)*
    *(amorphous silicates  \( \sim \) olivine \( \text{Mg}_x\text{Fe}_{2-x}\text{SiO}_4 \))*
  – *Infrared emission from dust grains + aromatic hydrocarbons*

(Draine 1999)
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 → 0.1 µm in size, containing ≥ 10000 atoms responsible for the FIR, sub-mm emission

very small grains → containing ≤ 100 atoms (less than10nm in size) responsible for a rising continuum ~10µm

PAHs (Polycyclic Aromatic Hydrocarbons) → benzene rings contain N ~ 50 atoms trace photodissociation regions.

Due to the size distribution of grains & 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

\[ I_ν \propto ε_ν B_ν(T) \]


Really hot dust (~200-1500K) in a equilibrium is observed via a near/mid-IR “bump” close to tori of AGNs.
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).
  - Normal Galaxies: L(mid_ir) ~ 20% L (IR) (Dale et al. 2001, Roussel et al 2001)
  - Active/Interacting galaxies: L(mid_ir) < ~5% L (IR) (Charmandaris et al. 2002)

- In normal late type galaxies most of their energy is released in the FIR.

- In AGN the high UV/X-ray flux can sublimate the grains and lead to destruction of PAH features and display a bump of thermal emission at 3-6microns and a power law spectrum.
A Hotter Dust Component

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 ([NeII] directly coupled to SF)
- Possible “bump” at 3-6 microns due to the hot dust of an AGN torus
The effects of radiation field in the Mid-IR

Flux Density normalised at 10μm

Rest Wavelength [μm]

NGC 7023
HII
PDR-H₂
M 17
An AGN in the MIR

Total spectrum of NGC1068

ISOCAM spectrum (diameter: 40")

AGN

[NeIII]

[NeV]

Starburst

[NeVI]

Le Floc’h et al. 2001 A&A, 367, 487
VV114: an AGN in Mid-IR
VV114: Nuclear spectra

PDR-like regions in the mid-IR
HII-like regions in the mid-IR
AGNs in the mid-IR

- Centaurus A (Sey 2) (100 pc)
- NGC 1068 (Sey 2) (650 pc)
- Arp 118 (Sey 2) (1700 pc)
- NGC 1365 (Sey 1.8) (950 pc)
- M 51 (Sey 2) (270 pc)
- NGC 1097 (Sey 1) (740 pc)
- Arp 236 (1800 pc)
SF in Interacting Galaxies

- Most galaxies are not isolated (Baade 1920)
- Our own Galaxy is interacting with the LMC and SMC!
- Interactions determine the morphology and evolution of galaxies
- Interactions drive gas into the nuclei and fuel supermassive BH.
- The galaxy merging rate increases with redshift $\sim (1+z)^m$, $m>2$

- Massive starbursts are obscured by dust:
  - hidden in the optical -> IRAS (Soifer et al. 1984)
  - most of the energy is emitted in far-IR
- Nearly all luminous IR galaxies are mergers (ie. Sanders 1988)

- ``Toomre’s merging sequence” is an ideal local sample.

- The optical/NIR morphology of interacting systems does not show where the “action” is (i.e. NGC 4038/39, Mirabel et al 1998)
NGC4038/39 in Mid-IR


The SED of LIGs

In the Mid-IR:

- we are less affected by absorption than in optical Av = 70*A (15µm)
- 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!

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)</th>
<th>LW4 (5.5-6.5 μm)</th>
<th>LW3 (12-18 μm)</th>
<th>LW2 LW4</th>
<th>LW3 LW2</th>
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Early stage interactions – pre-starburst phase

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

2. **NGC 3263**

3. **NGC 520**

4. **NGC 3256**

Charmandaris et al., 2001
Mergers/Merger remnants – post-starburst phase

5. NGC 6240

6. Arp 220

7. NGC 7252

8. NGC 3921

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

ISO: $15\mu m / 7\mu m$

IRAS $25\mu m / IRAS 12\mu m$

IRAS $60\mu m / IRAS 100\mu m$

Mid-IR imaging does reveal the intensity/age(?) of a starburst

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Sep 12th 2002
Arp299 (NGC3690/IC694)

HST V-band (Malkan et al 1998)
Arp299 – Morphology changes at Mid-IR

Background: HST J-band image
Contours: 
  a) 7 µm emission 
  b) 15 µm emission 
  c) 38 µm emission 

Arp299 – 38µm traces luminosity

Arp 299
$L_{IR} \sim 5.16 \times 10^{11} L_{\odot}$

IC694 => ~40% $L_{bol}$
NGC3690 => ~20% $L_{bol}$
Region C => ~10% $L_{bol}$

No evidence of AGN in Mid-IR neither in regions A nor B1
However, recent X-ray data suggest otherwise…
AGN / Starburst mid-IR diagnostic: low spectral resolution

AGN / Starburst mid-IR diagnostic: high spectral resolution

Mid-IR Spectral Diagnostics in ULIRGs

Mid-IR SED may depend on Seyfert type!

Fig. 7. The average rest-frame spectrum of the 20 best signal-to-noise ratio Sf1 galaxies. The silicate 9.7 μm feature appears in emission.

Fig. 8. The average rest-frame spectrum of the 23 best signal-to-noise ratio Sf2 galaxies.

Clavel et al. 2000, 357, 839
Laurent et al., A&A, 2000

AGN/Starburst Mid-IR diagnostic (2)
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<th>Source</th>
<th>RA (J2000)</th>
<th>DEC (J2000)</th>
<th>LW2 (mJy)</th>
<th>LW3 (mJy)</th>
<th>LW4 (mJy)</th>
<th>LW3/LW2</th>
<th>LW2/LW4</th>
<th>Spectral type</th>
<th>LW</th>
<th>CVF</th>
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<td>10221</td>
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<td>-00° 11' 00.8&quot;</td>
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<td>42</td>
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<td>73° 24' 03.3&quot;</td>
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<td>28</td>
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<td>-43° 01' 08.8&quot;</td>
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<td>1658</td>
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<td>-10° 19' 24.6&quot;</td>
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<td>2.59</td>
<td>1.05</td>
<td>AGN</td>
<td>–</td>
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</table>

| NGC 253 (Nuc : 7.5") (6) | 00° 47' 33.1" | -25° 17' 17.8" | 4703 | 15716 | 2296 | 3.34 | 2.05 | HII | HII |
| Arp 236 (Nuc : 4.5") (3) | 01° 07' 47.5" | -17° 30' 25.6" | 200 | 358 | 108 | 1.79 | 1.84 | PDR | AGN⁺ |
| NGC 1808 (Nuc : 9") (1) | 05° 07' 42.3" | -37° 30' 46.1" | 1074 | 1450 | 538 | 1.35 | 2.00 | PDR | PDR |
| M82 (Nuc : 9") (6) | 09° 55' 52.2" | -69° 40' 46.9" | 5198 | 12720 | 2573 | 2.45 | 2.02 | HII | HII |
| NGC 3256 (Nuc : 4.5") (1) | 10° 27' 51.8" | -43° 54' 08.7" | 442 | 1196 | 212 | 2.70 | 2.09 | HII | HII |
| Arp 299 (A : 4.5") (1) | 11° 28' 34.2" | 58° 33' 46.5" | 325 | 1860 | 108 | 5.73 | 3.00 | HII⁺ | HII⁺ |
| Arp 299 (B : 4.5") (1) | 11° 28' 31.5" | 58° 33' 40.4" | 505 | 1961 | 303 | 3.86 | 1.67 | HII | HII |
| Arp 299 (C : 4.5") (1) | 11° 28' 31.8" | 58° 33' 49.9" | 76 | 232 | 36 | 3.06 | 2.14 | HII | HII |
| Arp 299 (C : 4.5") (1) | 11° 28' 31.2" | 58° 33' 48.9" | 126 | 461 | 65 | 3.66 | 1.93 | HII | HII |
| NGC 4038 (Knot A : 6") (8) | 12° 01' 54.9" | -18° 53' 12.3" | 23 | 135 | 13 | 5.78 | 1.75 | HII | HII |
| Arp 220 (9) | 15° 34' 57.2" | 23° 30' 10.8" | 162 | 732 | 79 | 4.50 | 2.07 | HII | HII |
| NGC 6240 (9) | 16° 52' 58.5" | 02° 24' 03.4" | 229 | 758 | 107 | 3.30 | 2.14 | HII | HII |
| IRAS 17208-0014 (1) | 17° 23' 21.9" | -00° 17' 00.4" | 127 | 248 | 60 | 1.96 | 2.11 | PDR | – |
| IRAS 19254-7542 (1) | 19° 31' 21.6" | -72° 39' 20.2" | 111 | 264 | 84 | 2.37 | 1.33 | AGN⁺ | – |
| IRAS 20551-4250 (1) | 20° 58' 26.8" | -42° 39' 00.6" | 123 | 425 | 62 | 3.47 | 1.99 | HII | – |
| IRAS 23128-5919 (1) | 23° 15' 47.0" | -59° 03' 14.0" | 90 | 319 | 53 | 3.54 | 1.70 | HII | HII |

| NGC 253 (Disk) (1) | 00° 47' 33.1" | -25° 17' 17.8" | 339 | 681 | 171 | 2.00 | 1.98 | PDR | PDR |
| NGC 520 (1) | 01° 24' 43.8" | 03° 47' 30.8" | 456 | 511 | 231 | 1.05 | 2.10 | PDR | PDR |
| NGC 1068 (Disk) (2) | 02° 43' 40.6" | 00° 09' 47.8" | 246 | 296 | 137 | 1.20 | 1.80 | PDR | PDR |
| NGC 1808 (Disk) (1) | 05° 07' 42.3" | -37° 30' 46.1" | 1615 | 2694 | 728 | 1.67 | 2.22 | PDR⁺ | PDR |
| M 82 (Disk) (1) | 09° 55' 52.2" | 69° 40' 46.9" | 1177 | 1133 | 589 | 0.96 | 2.00 | PDR | PDR |
| NGC 3147 (5) | 10° 16' 53.6" | 73° 24' 03.3" | 375 | 483 | 215 | 1.29 | 1.74 | PDR | – |
| NGC 3256 (Disk) (1) | 10° 27' 51.8" | -43° 54' 08.7" | 202 | 420 | 85 | 2.07 | 2.38 | PDR⁺ | PDR⁺ |
| NGC 3263 (Nuc : 4.5") (1) | 10° 29' 31.3" | -44° 07' 22.0" | 50 | 62 | 31 | 1.03 | 1.94 | PDR | – |
| NGC 4676 (A) (1) | 12° 46' 10.1" | 30° 43' 57.2" | 58 | 30 | 40 | 0.53 | 1.44 | PDR⁺ | – |
| NGC 4676 (B) (1) | 12° 46' 11.4" | 30° 43' 23.1" | 4.11 | 2.15 | 2.17 | 0.52 | 1.89 | PDR | – |
| Centaurus A (Disk) (10) | 13° 25' 27.6" | -43° 01' 08.8" | 62 | 101 | 35 | 1.62 | 1.78 | PDR | PDR |
| NGC 6814 (6) | 19° 42' 40.6" | -10° 19' 24.6" | 291 | 290 | 144 | 1.00 | 2.02 | PDR | – |
| NGC 7252 (1) | 22° 20' 44.9" | -24° 40' 41.3" | 142 | 185 | 67 | 1.30 | 2.11 | PDR | – |
Absorption

How does absorption affect the form of the Mid-IR SED?

- **Arp 220**
  - H$_2$ (S5)
  - Silicate absorption
  - 6.2, 7.7, 8.6, 11.3

- **NGC 6240**
  - H$_2$ (S5), H$_2$ (S3)
  - 6.2, 7.7, 8.6, 11.3
  - 12.7 / [NII], [NIII]
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.

The overall morphology does not change much


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Sep 12th 2002
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

Beam effects in AGN classification: the case of Sy1 NGC6814
Application of the diagnostic...
Application of the diagnostic...
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.
- Even at short mid-IR wavelengths the morphology changes.
- None of the galaxies of the Toomre sequence presented shows AGN characteristics. However...
- …the absorption in mergers such as Arp220 is high so a based only on mid-IR data a weak enshrouded AGN can not be excluded in these systems.
Perspectives

◆ Current Caveats:
  – 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).
  – The 15µm range is not as “clean” to trace luminosity as the 35-45µm one.
  – Full spectral cubes are better than broad band images since we need to accurately measure the slope of the spectrum.
  – 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.

◆ Looking ahead: SIRTF (my sponsor!)
  – IRS: Higher sensitivity and wider spectral wavelength coverage (5-40 µm)
  – IRAC/MIPS: larger fields, mid-IR / far-IR imaging provide total energy content
  – IRS: Identify, measure their distance using the redshifted UIB features.
Infrared Spectrograph, J.R. Houck, Cornell, PI.
R=600 echelle spectrographs, 10-20 and 20-40 μm
R=60-120 long-slit spectrographs, 5-15 μm and 15-40 μm
Imaging/Photometry, 16 & 22μm
Si:As and Si:Sb IBC arrays, 128x128 pixel format
Perform spectroscopic observations of previously known sources (IRAS, ISO, 2MASS, etc.) and those discovered by SIRTF itself.

A selection of extragalactic science programs include:

- A study of the physical conditions of the atomic and molecular gas in dusty galaxies through the use of emission and absorption lines.
- A measurement of the redshifts of optically obscured, distant galaxies.

The IRS will enable spectroscopy at levels that are ~100 times more sensitive than those reached by ISO.
Circinus Galaxy has both high excitation lines from the AGN, and low excitation lines from early stars in the disk.
IRS spectral coverage / capabilities...

Sensitive to observe the UIB features of Arp220 up to $z=2$

IRS as a redshift machine!

Redshift of $\sim 2$ is interesting:

- Peak of the QSO luminosity function
- SIRTF (MIPS24$\mu$m & IRS) as well as Chandra (0.5-2keV) are most sensitive for starbursts in that distance
IRS spectroscopy at low z

Key Mid-IR diagnostic features

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<tr>
<th>Line</th>
<th>$\lambda_{\text{rest}}$</th>
<th>Ion Pot.</th>
<th>$z_{\text{in}}$</th>
<th>$z_{\text{out}}$</th>
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IRS high-res spectroscopy at low z

- ISO SWS: 2–10 hrs per source. Line flux limits ~ 1–few x 10^{-21} W cm^{-2}
- IRS: 3-5σ detection to 10^{-22} W cm^{-2} in about 500 sec in Hi-res mode.

  - At z=0.1, the ISO NeV limit in Arp220 corresponds to ~10^{-22} W cm^{-2}
    (Mrk 273 would have a NeV line flux of ~ 10^{-21} W cm^{-2})

  - At ~3300 sec / target, we can obtain low and high res spectra at the 1 mJy
    (10 µm) and 10^{-22} W cm^{-2} (15 µm) levels, including all overheads.

  - There are hundreds of IRAS sources that could be measured with the
    IRS and placed upon mid infrared line diagnostic diagrams.
Very dusty sources at low-z, such as Ultraluminous Infrared Galaxies, have
rest frame mid infrared (10 µm) -to- UV (2500–3000Å) flux density ratios of:

~ 200:1 for cool sources (e.g. Arp 220)
~1000:1 for warm sources (e.g. IRAS 09104+4109)

An optically faint, warm ULIRG with R=26* mag (11.1 x 10^{-8} Jy) at z=2 can be
detected in a low resolution IRS spectrum at the 3σ level in only 3.5 hrs.
This same warm source would be a 5σ detection with MIPS after only 2000
sec. A cool ULIRG-like galaxy would require about 110 hrs of integration to
be detected in a low resolution IRS spectrum at the 3σ level.

* A system with R=26 is about 5-10x fainter than expected for a ULIRG at z=2
  with L_{bol} = 10^{12} L_{☉}.
How does one select the enshrouded distant sources?


2. Select among known sources detected in X-rays / sub-mm / far-IR which have no optical / near-IR counterparts.

- Apply the second method to mid-IR bright sources (~0.5mJy at 15µm) and then use the detected sources as a control sample for the development of a mid-/far-IR photometric redshift method.

A “cheap” way of doing so is using the IRS peakup cameras. (In 700sec 1σ~25µJy @16&22µm)
M82 spectrum for z = 0.3, 1, 2 and 3

Selecting the right sources (2)
IRS Peakup colors

Signal ratio for Blue/Red Peakup camera

- 16µm / 22 µm

T. Herter, for the IRS Science Team

VC - Yale
The above figure shows the IDL interface to the IRS simulator. For a given template spectrum a user can specify redshift, integration time, ecliptic latitude, flatfield uncertainty, and the average flux in the 25 µm IRAS band.

The figures to the right show the simulated results as expected from the high- and low-res IRS modules. Note how the 6.2, 7.7 and 8.6 µm emission features dominate the IRAS filter band thus providing a powerful tool for redshift determination.

*kindly provided by E. Sturm et al. (MPE)
As in the previous panel the figures show the IDL interface to the IRS simulator and the expected results from the high- and low-res IRS modules for a prototypical AGN at high redshift. Note that the specified integration times are on-source times per module. The spectrum is dominated by the hot dust continuum emission while the mid-IR emission features are not detectable. However, the silicate absorption around 9.6 \( \mu m \) can be clearly identified.

*kindly provided by E. Sturm et al. (MPE)
As evident from a comparison between the HST and ISO images of the HDF the spatial correlation of individual sources is problematic. Direct redshift determinations from the mid-IR spectrum of individual sources as faint as ~0.5 mJy would provide:
- an unbiased method to derive number counts of star forming galaxies as a function of redshift
- an important calibration sample for mid/far-IR photometric redshift determinations of even fainter galaxies.

The pronounced mid-IR emission or absorption features can be used as redshift diagnostics with the IRS low-res module.
The ISOCAM 15 µm surveys yielded a high density of mid-IR sources which are bright enough for spectroscopic redshift determinations.

The HST Deep Field North superimposed with the ISOCAM 15 µm fluxes (yellow contour lines) and the positions of the 7 µm ISOCAM sources (green circles) [Aussel et al., 1999, A&A 342, 313].

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<table>
<thead>
<tr>
<th>Survey Name</th>
<th>$N_{\text{obs}}$</th>
<th>Area (am²)</th>
<th>$S_{\text{80%}}$ (mJy)</th>
<th>$t_{\text{int}}$ (min)</th>
<th># gal</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lockman Shallow(a)</td>
<td>3</td>
<td>1944</td>
<td>1</td>
<td>3</td>
<td>80</td>
<td>$-2.1 \pm 0.2$</td>
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<tr>
<td>Lockman Deep(a)</td>
<td>6</td>
<td>510</td>
<td>0.6</td>
<td>11</td>
<td>70</td>
<td>$-2.4 \pm 0.3$</td>
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<tr>
<td>MFB Deep(a)</td>
<td>18</td>
<td>710</td>
<td>0.4</td>
<td>15.4</td>
<td>141</td>
<td>$-2.4 \pm 0.2$</td>
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<tr>
<td>Marano UD(a)</td>
<td>75</td>
<td>70</td>
<td>0.2</td>
<td>114</td>
<td>82</td>
<td>$-1.5 \pm 0.1$</td>
</tr>
<tr>
<td>MFB UD(a)</td>
<td>75</td>
<td>90</td>
<td>0.2</td>
<td>114</td>
<td>100</td>
<td>$-1.5 \pm 0.2$</td>
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<tr>
<td>HDF North(b)</td>
<td>64</td>
<td>27</td>
<td>0.1</td>
<td>135</td>
<td>44</td>
<td>$-1.6 \pm 0.2$</td>
</tr>
<tr>
<td>HDF South(a)</td>
<td>64</td>
<td>28</td>
<td>0.1</td>
<td>168</td>
<td>63</td>
<td>$-1.4 \pm 0.1$</td>
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<tr>
<td>A2390(c)</td>
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<td>5.3</td>
<td>0.05</td>
<td>432</td>
<td>31</td>
<td>$-1.2 \pm 0.6$</td>
</tr>
</tbody>
</table>
Summary

- SIRTF will detect thousands of ULIRGs to high redshifts (z=1-5).
  
  *Hundreds (thousands ?) of sources per sq. degree ?*

- Classification of these sources will be done via MIPS and IRAC colors, and comparison with ground/space based optical data.

- Redshifts of the dustiest sources will be obtained with the IRS.

- Mid-IR spectral classifications of hundreds of low-z IRAS sources (z < 0.5) will be performed with the IRS.