Dust and **mid-IR** properties in luminous IR galaxies:
From IRAS to ISO to SIRTF

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*6th Hel.A.S. Meeting – September 16th 2003*

*Until 19th Sep. 2003 @ 535 Μ/Κ ΤΠ*
Goals of the talk

- Briefly remind us what we know about IR Luminous Galaxies
- Describe how we try to study the properties of their IR radiation emphasizing on results of the Infrared Space Observatory (ISO)
- Demonstrate some of the limitations we are facing
- End with a hopeful note about what we’ll discover in the near future

Some important dates in IR astronomy:

- January 1983 – IRAS, the InfraRed Astronomical Satellite is launched
- The first IR galaxy is discovered within the first ~hrs of observations! [NGC6543 (PN) & NGC6552 (Sy2) 6arcmin away]
- IRAS minisurvey reveals 9 sources with $L_{\text{IR}}/L_B >50$ and no optical POSS counterparts (Houck et al. 1984) → faint galaxies at z~0.2-1 → IR selected galaxies have high luminosity (Soifer et al. 1984)
- November 1995 – The Infrared Space Observatory (ISO) is launched
- **August 25, 2003 01:37am** – SIRTF, the Space InfraRed Telescope Facility is launched to study those faint extragalactic sources.
Dust and the problem of extinction

The Universe is dusty!

Dust grains are formed in the envelopes of evolved stars (giants, SNe, etc)...

... they absorb the UV/optical radiation and they reemit it in the IR.
Dust in the distant Universe

* Detection of the diffuse extragalactic background by DIRBE/COBE - 75% of which is associated with IR luminous galaxies

* The effects of extiction are extremely important in the distant Universe

* Observations in the optical are not sufficient to understand the dominant physical mechanisms

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Extragalactic IR in 1971

At infrared wavelengths beyond 20 µm we know nothing about the emission from any star but the Sun. In some H II regions, in the galactic nucleus, and in NGC 1068, we see tantalizing evidence of luminosities comparable to or greater than that emitted in the rest of the observed spectral regions. Of the three decades of the electromagnetic spectrum covered by the infrared, only one decade has been explored; the exploration of the other two is certain to give us new and different challenges.

Number of extragalactic sources detected at 10µm:
1971 → 13 (Neugebauer et al. ARA&A)
1978 → ~100 (Rieke & Lebofsky ARA&A)
1988: → IRAS PSC ~250,000 entries (~75,000 CGQ)
Figure 12: Atmospheric transmission for Mauna Kea and MIRLIN’s filter passbands.
The Advantages of Space:

100% Transmission and a One-Million Fold Decrease in Sky Brightness.

The outer Space is cold!
IRAS discovers IR Luminous Galaxies

What we know on ULIRGs since 1984

- \(L_{\text{IR}} > 10^{12} L_\odot\)
- \(L_{\text{bol}} \sim L_{\text{IR}}\) and \(L_{\text{opt}} < 0.1 L_{\text{IR}}\)
- > 90-95% are interacting or in merging systems
- Often have very strong emission lines (atomic, molecular, PAH)
- Can have unusually strong stellar CO absorption
- Large, compact reservoirs of molecular gas (\(> 10^9 - 10^{10} M_\odot\) over \(\leq 1\) Kpc) in the nuclei
- Can drive “superwinds” of hot, enriched gas into the IGM
- Rare in the local Universe - only \(~3\)% of galaxies in BGS

Big Q: What Powers ULIRG’s ??

- A starburst (SFR \(\sim 10-100 M_\odot\)yr \(^{-1}\)), an AGN, or both ?
- ISO gave some indications - SIRTF/IRS will provide the answer with ~80hrs of observing time!..
IRAS and the IR Luminous Galaxies

I - Introduction

Infrared UV

$L(8-100\mu m) > 10^{11} L_{\odot}$

(Sanders & Mirabel 1996)

Devriendt et al. 1999

Infrared

(Mirabel et al. 1991)
ULIRGs are interacting systems

*Figure 4* Optical ($r$-band) CCD images of the complete sample of ten ULIRGs from the original BGS (Sanders et al 1988a). Tick marks are at 20'' intervals.
ULIRGs are multiple interacting systems

Borne et al 2000
ULIRGs dominate the high luminosity galaxy population in the local Universe

LIRGs and ULIRGs are responsible for ~2% of the L(IR) at z~0 but for >75% at z~1 (Elbaz et al. 2003)

Figure 1  The luminosity function for infrared galaxies compared with other extragalactic objects. References: IRAS RBGS (Sanders et al 1996a), IRAS 1-ly Survey of ULIRGs (Kim 1995), Palomar-Green QSOs (Schmidt & Green 1983), Markarian starbursts and Seyfert galaxies (Huchra 1977), and normal galaxies (Schechter 1976). Determination of the bolometric luminosity for the optically selected samples was as described in Soifer et al (1986), except for the adoption of a more accurate bolometric correction for QSOs of $11.8 \times \nu L_\nu (9.43 \mu m)$ (Elvis et al 1994).
NGC4038/39 in Mid-IR


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: $A_V \sim 30$ mag $\rightarrow$ 1 photon in $10^{12}$ penetrates
    $A_{2.2\,\mu m} \sim 2.5$ 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 $Mg_xFe_{2-x}SiO_4$
  – Infrared emission from dust grains
    + aromatic hydrocarbons

(Draine 1999)
Doing some physics: 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 than 10nm 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

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

Power-law emissivity: \( \varepsilon_\nu \propto \nu^n \) (i.e. Dale et al, ApJ, 2001)

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 \( \sim 0.1 - 1 \% \))
  - 50\% of gas heating is due to grains of sizes < 15 Å

- Subsequently the gas cools via far-IR emission lines (\([\text{OI}] 63 \ \mu\text{m}, \ [\text{CII}] 158 \ \mu\text{m}\))

- Process of randomly heating dust grains to high T (\(\sim 1000\text{K}\)) for short periods (\(\sim 1\text{s}\))
  - Not in equilibrium.

- PAHs, dominate the mid-IR (5-20 \(\mu\text{m}\)) flux in normal galaxies and quiescent star forming regions via the so-called Unidentified IR Bands (UIBs) or IR Emission Features (IEFs).
  - Normal Galaxies: \(L(\text{mid}_{\text{ir}}) \sim 20\% \ L(\text{IR})\) \(\text{\cite{Dale, Roussel}}\)
  - Active/Interacting galaxies: \(L(\text{mid}_{\text{ir}}) < \sim 5\% \ L(\text{IR})\) \(\text{\cite{Charmandaris}}\)

- 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.
Energy Balance

Log [CII]/νf(5-10μm)

σ=0.18 dex

Log [CII]/FIR

σ=0.37 dex

Log f_ν(60μm)/f_ν(100μm)
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
An AGN in the MIR

Le Floc'h et al. 2001 A&A, 367, 487
AGN / Starburst mid-IR diagnostic: low spectral resolution

AGN / Starburst mid-IR diagnostic: high spectral resolution


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AGN/Starburst Mid-IR diagnostic

Laurent et al., A&A, 2000
Beam effects in AGN classification: the case of Sy1 NGC6814
Application of the diagnostic...
Provide the final answer to the issue of AGN power by probing their mid-IR signature in the local and distant Universe

SIRTF (25 August 2003)
◆ **Infrared Great Observatory**
  - *Background Limited Performance 3 -- 180um*
  - 85 cm f/12 Beryllium Telescope, $T < 5.5K$
  - 6.5um Diffraction Limit
  - New Generation Detector Arrays
  - **Instrumental Capabilities**
    - Imaging/Photometry, 3-180um
    - Spectroscopy, 5-40um
    - Spectrophotometry, 50-100um
  - *Planetary Tracking, 1 arcsec/sec*
  - >75% of observing time for the General Scientific Community
  - 2.5 yr Lifetime/5 yr Goal
  - Launch in Aug. 2003 (Delta 7920H)
  - Solar Orbit
  - $650 M Development Phase Cost Cap

◆ **Cornerstone of NASA’s Origins Program**
The Sensitivity of Infrared Telescopes

Current State-of-the-Art

IRAS

SIRTF

WAVELENGTH (um)

LIMITING FLUX \( F (\text{mJy}) \)
The IR Spectrograph of SIRTF

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 & 22 µm
Si:As and Si:Sb IBC arrays, 128x128 pixel format
Circinus Galaxy has both high excitation lines from the AGN, and low excitation lines from early stars in the disk.
**IRS spectroscopy at low/high z**

**Key Mid-IR diagnostic features**

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IRS spectral coverage / capabilities...

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

IRS as a redshift machine!

Redshift of ~2 is interesting:

- Peak of the QSO luminosity function
- SIRTF (MIPS24µm & IRS) as well as Chandra (0.5-2keV) are most sensitive for starbursts in that distance
How Luminous are these distant ULIRGs?

An “M82-like” galaxy at \( z=1 \)

- \( F(15\mu m)=1\text{mJy} \)
- \( L(8-1000\mu m) \approx 6 \times 10^{12} \text{L}_\odot \)

An “M82-like” galaxy at \( z=2 \)

- \( F(15\mu m)=1\text{mJy} \)
- \( L(8-1000\mu m) \approx 5 \times 10^{13} \text{L}_\odot \)

A “NGC1068-like” galaxy at \( z=1 \)

- \( F(15\mu m)=1\text{mJy} \)
- \( L(8-1000\mu m) \approx 1.2 \times 10^{12} \text{L}_\odot \)

A “NGC1068-like” galaxy at \( z=2 \)

- \( F(15\mu m)=1\text{mJy} \)
- \( L(8-1000\mu m) \approx 1 \times 10^{13} \text{L}_\odot \)

\( H_0=75/\text{km/s/Mpc} \)
\( \Omega_\Lambda=0.7, \quad \Omega_M=0.3 \)

Will we detect a new population of dust enshrouded Hyperluminous \( \log(L_{IR})>13 \). IR Galaxies?
Currently only \( \sim 30 \) such systems are known based on follow-up of IRAS and sub-mm/SCUBA detection.
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.