Luminous Infrared Galaxies

FIRSED
April 3, 2013
The Great Observatories All-sky LIRG Survey (GOALS)

- IRAS-detected galaxies with $f_{60\mu m} > 5.24 \text{ Jy } & |b| > 5^\circ$
- 201 galaxies with $L_{IR} \geq 10^{11.0} \text{ L}_\odot$
- HST, Chandra ~ 88 LIRGs; Spitzer, Galex, Herschel ~ 201 LIRGs
- http://goals.ipac.caltech.edu
Luminous & Ultraluminous Infrared Galaxies

- LIRGs: $L_{\text{IR}}[8-1000 \ \mu \text{m}] \geq 10^{11-11.99} \ L_\odot$
- ULIRGs: $L_{\text{IR}} \geq 10^{12} \ L_\odot$

- Spiral galaxies which show an increasing tendency to be involved in interactions or mergers with increasing luminosity

- Rich in optically-visible star clusters

NGC 5257/8
Luminous & Ultraluminous Infrared Galaxies

- Spiral galaxies which show an increasing tendency to be involved in interactions or mergers with increasing luminosity
- Rich in optically-visible star clusters
- Rich in dust, and both neutral and star-forming molecular gas

Contours = HI

CO(1 → 0)
Luminous & Ultraluminous Infrared Galaxies

- Spiral galaxies which show an increasing tendency to be involved in interactions or mergers with increasing luminosity
- Rich in optically-visible star clusters
- Rich in dust, and both neutral and star-forming molecular gas
- Evidence of Active Galactic Nuclei (AGN) activity
U/LIRGs and luminosity function

- The local space density of LIRG is low
- and overtakes that of normal galaxies beyond a $L_{\text{bol}} \sim 10^{11.4} L_{\odot}$
The high end luminosity of the LIRG population lie above the main sequence with SFR ~ 100s...

... if the IR is tracing only star formation
Ultraluminous IR Galaxies & the evolution of QSOs?

Gas-rich Disk Progenitors with seed SMBH

(Sanders et al. 1988)
Ultraluminous IR Galaxies & the evolution of QSOs?

Enhanced Star Formation; SMBH building

(Sanders et al. 1988)
Ultraluminous IR Galaxies & the evolution of QSOs?

(Sanders et al. 1988)
Evolutionary byproduct

Elliptical/SO Galaxy

(e.g., Barnes & Hernquist 1992)
Gas-rich Progenitors

Starburst/AGN; Dust-enshrouded phase; cool IR colors

Dust-clearing; AGN-dominant phase; warm IR colors

Elliptical Byproduct
SED evolution: Cool → Warm

\( f_{25\mu m}/f_{60\mu m} < 0.20 \) (Dust-enshrouded phase)

\( f_{25\mu m}/f_{60\mu m} \geq 0.20 \) (Dust-clearing phase)
The importance of IR for LIRG studies

- \( \frac{V_{\text{IR}} L_{\text{IR}}}{V_{\text{opt}} L_{\text{opt}}} \uparrow \text{ as } L_{\text{bol}} \uparrow \)

(Sanders & Mirabel 1996): see Vivian U’s talk for an update
The importance of IR for LIRG studies

- The SFR(UV) vs. SFR(IR) discrepancy grows with increasing $L_{\text{IR}}$

(Howell et al. 2010)
An imaging census of light from a LIRG

- Unobscured massive star formation

(HST Far-UV)

(Inami et al. 2010)
HST Optical

- Unobscured star formation

(Inami et al. 2010)
HST Optical

- Unobscured star formation

(Kim et al. 2013)
HST NIR

- embedded NRG sources + old stellar population

(Inami et al. 2010)
5 kpc

Spitzer mid-IR
- Embedded Star Formation & AGN
- Dust emission

From the number of bright star clusters surround the II Zw 096 nuclei and are present throughout the merging disks (see Figure 2).

88 are detected in the FUV and limits of 26.0 mag and 25.5 mag, respectively. Of these, 97 and 17 9m a g.

The high-resolution AKARI near-infrared spectrum of source C+D (see Figure 3). The full low-resolution spectrum is at the top left, while a close-up of the SL spectrum is shown at the bottom left. The SH and LH spectra are shown at the top right and the bottom right, respectively. Some residual order tilting is evident in the two reddest orders of LH. All lines are not resolved.

The spectrum of sources C and D taken with Spitzer mid-IR imaging data show that a large region of diffuse emission. For all clusters, we use a 0.1 r a d i u s c i r c u l a r aperture, depending on the location in the FUV image to avoid crowded regions. We additionally show the colors of a number of diffuse emission regions throughout the merger system. For the diffuse emission, we identify 128 clusters with 3.6% completeness.

We derive a ratio of $F_{PAH}/F_{BR}$ of 0.08 and 0.03 for the PAH and the Br$^{+}$ emission, respectively. The 3.6% line flux is (0.01 ± 0.08) W m$^{-2}$ µm$^{-1}$.

The spectrum of source A (not shown) also exhibits $[NeII]$, while no [SIV] emission lines are detected. The line fluxes are $\sim 0.003$ W m$^{-2}$ µm$^{-1}$ and an EQW of 0.08 ± 0.05 W m$^{-2}$ µm$^{-1}$.

Since the continuum emission at 3.6µmP A H.$\alpha$, respectively, after fitting both with a Gaussian function (see Tables 3 and 4). The EQW of the [NeII] line is not resolved.

The spectrum of source C+D is shown in Figure 7. Strong $[SiII]$ emission contribution from the overlap wavelengths of SL and LL has a difference less than 0.06 W m$^{-2}$ µm$^{-1}$.

The spectrum of source D (see Figure 3). The full low-resolution spectrum is at the top left, while a close-up of the SL spectrum is shown at the bottom left. Some residual order tilting is evident in the two reddest orders of LH. All lines are not resolved.

Spitzer mid-IR
- Embedded Star Formation & AGN
- Dust emission

(Inami et al. 2010)
Spitzer mid-IR

- Embedded Star Formation & AGN
- Dust emission

(Inami et al. 2010)
Chandra X-ray

- Embedded Star Formation & AGN

(K. Iwasawa et al.: C-GOALS survey)

Energy (keV)

5 kpc

(Inami et al. 2010)
JVLA

- Embedded Star Formation & AGN

(Barcos et al. 2013)
ALMA

- Dust continuum distribution
- Star-forming molecular gas tracers

(Stierwalt et al. 2013)
Isolated System?
Mid-Stage - progenitors intact

NGC 5257/8
Mid-Stage - overlapping disks, double AGN + outflow

(Mazzarella et al. 2012)
Late Stage - single nucleus, weak AGN

NGC 2623

(Evans et al. 2008)
The utility of IR/submm/radio emission

• assessment of the ionization mechanisms/source(s) in obscured regions and the optical depth towards these regions

• assessment of the physical state in molecular clouds

• measurement of the physical sizes of active regions and thus the IR surface brightness

• measurement of the kinematics of the gas, and thus a assessment of rotation (e.g. for dynamical mass estimated) and importance of infall/outflow in obscured regions

...at wavelengths that are energetically important
• JWST, ALMA and JVLA provide sub-” resolution
The utility of IR/submm/radio emission

1. Spitzer: AGN/Starburst diagnostics (see Veilleux’s talk)
2. Herschel: the [C II]/FIR decrement
3. Herschel: CO SLED
4. ALMA: CO(6→5) emission
(1) AGN-Starburst diagnostics: ISO data

[Graphs showing relative strength of 7.7μm PAH feature vs. high/low ionization, indicating destruction by AGN.] (Genzel et al. 1998)
AGN-Starburst diagnostics

ISO

(Genzel et al. 1998)
Fig. 1.—IRS Short-Low and Long-Low spectra of the 10 BGS ULIRGs in order of decreasing $25\mu m$ flux density. Prominent emission features and absorption bands (the latter indicated by horizontal bars) are marked on representative spectra. Not all features are marked on all spectra; see Tables 3 and 4 for measured features. Expanded views of the $5\gamma_{14}/C_{22}\mu m$ regions (Short-Low) of each spectrum are shown at the end.

Fig. 2.—ISOPHOT-S spectra ($j^*/j^*D_{90}$) of 15 ULIRGs. Observed wavelengths are shown at the top and rest wavelengths at the bottom of each spectrum. Flux densities (not including the correction for chopped mode of a factor of $D_{1.4}$) are in janskys. Error bars as provided by PIA are shown for UGC 5101.

(Genzel et al. 1998; Armus et al. 2007)
AGN-Starburst diagnostics

- E.g., Strength of PAH anti-correlated with AGN strength
  (Armus et al. 2007)

Spitzer PAH absorption by ionizing source

rest wavelength (microns)
AGN-Starburst diagnostics

- E.g., [Ne V] / [Ne II] correlated with AGN strength (Armus et al. 2007)
Spitzer IRS: AGN vs. starburst diagnostics

- Mid-IR diagnostics used: [NeV]/[NeII], [OIV]/[NeII], 6.2 μm PAH EQW & MIR continuum ratios (e.g., Veilleux et al. 2009)
- Punchline 1: Based on the MIR: 10% of local LIRGs have dominant AGN
- Punchline 2: AGN are responsible for 12% of $L_{IR}$ of LIRGs in the local Universe
- Is the mid-IR a sufficiently long wavelength to diagnose AGN/starburst fractions?

(Petric et al. 2011; see Veilleux’s talk for more in-depth discussion)
(2) The $[\text{C II}]$ 158$\mu$m/FIR decrement in ULIRGs

- $L_{[\text{C II}]}$ is $\sim 1\%$ of $L_{\text{FIR}}$ in normal, star-forming galaxies
- Major coolant in the neutral ISM
- Ionization potential $= 11.26$ eV

(e.g., Luhman et al. 2003)
[C II]/FIR vs. the star formation efficiency

- [CII]/FIR ↓ as the star formation efficiency ↑
- Similar decrements are seen for other forbidden submm lines

(Gracia-Carpio et al. 2011)
low [C II]/FIR galaxies have high ionization parameters (U)

- as inferred from the [OIII] / [NII]
- and dust temperature

(Zhao et al. 2013; Diaz-Santos et al. 2013; see also Abel et al. 2009; Gracia-Carpio 2011)
low [C II]/FIR galaxies are optically thick

- [CII]/FIR ↓ as optical depth ↑

(Diaz-Santos et al. 2013; spectra - Brandl et al. 2006)
low [C II]/FIR galaxies have compact IR-emitting regions

- [CII]/FIR ↓ as the compactness of the MIR emission ↑

(Diaz-Santos et al. 2013)
• As $U \uparrow$, the gas opacity in the HII regions $\downarrow$
• chance of **UV photons $\rightarrow$ dust $\rightarrow$ FIR photons** high, especially if the starburst region is optically thick
U/LIRGs with high SSFRs

... form their stars in warm, compact, optically thick regions

(Diaz-Santos et al. 2013)
ULIRGs with high SSFRs

... form their stars in warm, compact, optically thick regions (Elbaz et al. 2011)
U\LIRGs with high SSFRs

α is correlated with radio extent

... form their stars in warm, compact, optically thick regions

(Murphy et al. 2013)
• Transitions up to $J = 14 \rightarrow 13$ observed
• Model: dense gas clump in a 560 pc radius star-forming disk exposed to UV + X-rays from an AGN heating the inner 160 pc.

(van der Werf et al. 2010)
The Herschel-ALMA Overlap

(van der Werf et al. 2010)
5 kpc

• >95% of the emission centered on a single, resolved source
• If the molecular gas is distributed in a rotating disk, $M_{\text{dyn}} = 3.3 \times 10^9 \, M_{\odot}$

(Inami et al. 2010; Stierwalt et al. 2013)
ALMA observations of IIZw096

<table>
<thead>
<tr>
<th>Source</th>
<th>$L_{\text{IR}}$ ($L_\odot$)</th>
<th>size (pc)</th>
<th>$\mu_{\text{IR}}$ ($L_\odot$ kpc$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIZw096</td>
<td>$7\times10^{11}$</td>
<td>277x185</td>
<td>$4.3\times10^{12}$</td>
</tr>
<tr>
<td>Orion core</td>
<td>$2\times10^{5}$</td>
<td>0.3</td>
<td>$3\times10^{12}$</td>
</tr>
<tr>
<td>M82</td>
<td>$3\times10^{10}$</td>
<td>450x75</td>
<td>$9\times10^{11}$</td>
</tr>
</tbody>
</table>

(Inami et al. 2010; Stierwalt et al. 2013)
outflows: e.g., SMA results

- gas disk has an inner region with significant outflow motion and outer region dominated by rotation
- dense absorbing gas deep within the gas disk
- source of acceleration - mechanical energy from supernovae or radiation pressure from an AGN

(Sakamoto et al. 2009)
Summary

- ULIRGs have complex substructures which vary as a function of wavelength.

- Mid-IR diagnostics has provided insight to the relative importance of starburst and AGN to the IR output of ULIRGs.

- At the high luminosity end, the star formation in ULIRGs is compact and highly dust-enshrouded.

- ALMA will enable the study of the star-forming molecular gas and dust, the importance of starburst and AGN heating to the chemistry observed in molecular clouds, the extent of the star-forming regions, the feedback in the form of molecular outflows.