Understanding Luminous Infrared Galaxies in the *Herschel* Era

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Collaborators: Jason Chu (IfA), Kirsten Larson (Caltech/IPAC), Joseph Mazzarella (Caltech/IPAC), Lisa Kewley (ANU)
Understanding submm-selected LIRGs in the Herschel Era

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I. $Z \sim 0$ (PACS+SPIRE) The Herschel-GOALS atlas

II. $Z \sim 2.3$ (BPT diagram) Herschel vs. MOSDEF selection
Why Study Luminous IR Galaxies?

- Hundreds of luminous infrared galaxies (LIRGs) first discovered in the 1980s.

- They emit the bulk of their bolometric luminosities in the infrared: $L_{\text{IR}} = L(8-1000 \, \mu\text{m})$.
  - LIRG: $11 \leq \log(L_{\text{IR}}/L_{\odot}) < 12$
  - ULIRG: $12 \leq \log(L_{\text{IR}}/L_{\odot}) < 13$

- Many are interacting/merging

- (U)LIRGs much more common in the high-$z$ universe (detected as SMGs).
• Consists of the 201 brightest galaxies in the Revised Bright Galaxy Sample (RBGS) with $L_{\text{IR}} \geq 10^{11} L_\odot$.

• GOALS is a statistically complete, flux-limited local sample of infrared luminous galaxies.

• They represent a complete picture of galaxy evolution in the local universe.

 ➔ Critical to study these galaxies in the FIR/submm, where they emit the bulk of their bolometric luminosity.
I. *Herschel*-GOALS Observations

- Entire GOALS sample imaged by PACS and SPIRE (PI: Sanders).
- Photodetector Array Camera and Spectrometer (PACS)
  - $70 \mu m \rightarrow 5.6''$ beam FWHM
  - $100 \mu m \rightarrow 6.8''$
  - $160 \mu m \rightarrow 11.4''$
- Spectral and Photometric Imaging Receiver (SPIRE)
  - $250 \mu m \rightarrow 18.1''$
  - $350 \mu m \rightarrow 25.2''$
  - $500 \mu m \rightarrow 36.6''$
The Herschel-GOALS Atlas

- Maps of all 201 GOALS systems have been published for all six Herschel bands in Chu et al. (2017).
- Aperture photometry measured for every GOALS object:
  - Total system fluxes.
  - Component fluxes where possible.
- Very good signal to noise ratios:
  - PACS: Typical $S/N\sim 10-20$
  - SPIRE: Typical $S/N\sim 5-15$

Data: http://irsa.ipac.caltech.edu/data/GOALS/galaxies/
Results: Infrared SEDs of (U)LIRGs

11.00 < log($L_{IR}/L_{Sun}$) < 11.25

11.25 < log($L_{IR}/L_{Sun}$) < 11.50

11.50 < log($L_{IR}/L_{Sun}$) < 11.75

11.75 < log($L_{IR}/L_{Sun}$) < 12

12.00 < log($L_{IR}/L_{Sun}$) < 12.25

12.25 < log($L_{IR}/L_{Sun}$) <

(Chu+ 2017bc, in prep.)
Results: Infrared SEDs of (U)LIRGs

IRAS

(Chu+ 2017bc, in prep.)
Results: Infrared SEDs of (U)LIRGs

IRAS + Spitzer + WISE

(Chu+ 2017bc, in prep.)
Results: Infrared SEDs of (U)LIRGs

IRAS + Spitzer + WISE + Herschel

(Chu+ 2017bc, in prep.)
Results: Infrared SEDs of (U)LIRGs

• SED peak:
  - Becomes brighter, with significant jump at highest $L_{\text{IR}}$.
  - Peak is at shorter wavelengths with increasing $L_{\text{IR}}$.

• FIR/sub-mm spectral index:
  - GOALS: Nearly constant at all $L_{\text{IR}}$ at $\lambda\geq250$ $\mu$m, $F \propto \nu^{4.05\pm0.12}$.
  - Sub-LIRGs less steep.
  - x2 extra jump in luminosity at $L_{\text{IR}}$ at $\lambda\geq60$ $\mu$m in highest bin.

• MIR (30-70 $\mu$m) spectral index:
  - Relatively constant for all GOALS bins, except two highest bins.
Results: Comparison to Model SEDs

- We compared our median SEDs to the model predictions of Chary & Elbaz (2001).

- CE01 produced SED templates of galaxies as a function of IR luminosity using IRAS, ISO, and SCUBA data.

Chu et al., (2017b, in prep.)
Results: Comparison C+17 to CE01 Model SEDs

- In the FIR/sub-mm, CE01 slightly underestimates flux in some bins, while in others it overestimates.

- In the MIR, CE01 matches the data well except in highest $L_{\text{IR}}$ bins where it overestimates.
Results: Far-Infrared Colors

- Plot of far-IR flux ratios as a function of $L_{IR}$, including the following SED templates:
  - Chary & Elbaz (2001)
  - Rieke et al. (2009)

- Comparison with models:
  - R09 predicts the KINGFISH galaxies well, except the 70/100 color.
  - CE01 predicts the KINGFISH galaxies well, except the 70/250 color.
  - Both models over-predict the 70/250 color for the GOALS galaxies.

Chu et al., (2017b, in prep.)
II. Optical Line Diagnostics of (U)LIRGs

• Powerful tool to study a galaxy’s ISM conditions.
• Uses optical emission line flux ratios to separate starburst and AGN galaxies:
  • $\text{[O III]} \lambda 5007 / \text{H} \beta$
  • $\text{[N II]} \lambda 6583 / \text{H} \alpha$
  • $\text{[S II]} \lambda \lambda 6717, 6731 / \text{H} \alpha$
  • $\text{[O I]} \lambda 6300 / \text{H} \alpha$
• Theoretical classification lines:
  • Kewley+ 2001 proposed first set of theoretical BPT classification lines for $z=0$.
  • Kewley+ 2013a produced theoretical classification lines up to $z=3$.

Where do (U)LIRGs at $z\sim2.3$ lie on the BPT diagram?
$z \sim 2.3$ Redshift Distribution

![Secure Redshifts on BPT Plot](image-url)

- IR–Selected (MIR + FIR)
- Star–Forming (sBzK)
- All Galaxies
$z \sim 2.3$ Stellar Mass Distribution

Stellar Mass Distribution on BPT Plot

Number of Galaxies

log(M/M$_{\text{Sun}}$)

IR–Selected (MIR + FIR)  
Star–Forming (sBzK)  
All Galaxies

$z \sim 2.3$ Stellar Mass Distribution
Optical Line Diagnostics of (U)LIRGs @ $z \sim 2.3$

- Sample selected from COSMOS field:
  - (U)LIRGs selected by their 24 $\mu$m and/or Herschel detections.
  - Normal star-forming sBzK galaxies.
  - Photometric redshift cut between $2 < z < 2.61$.
  - Complementary to rest-frame optically selected samples of MOSDEF and KBSS.

- Observations using Keck MOSFIRE (PI: Chu)
  - 7 nights (1 lost to weather) in H+K band.
  - 400 objects total observed.
  - 307 objects with secure redshifts.

- Results:
  - The sBzK galaxies coincide with the results from Steidel+ 2014 and Shapley+ 2015.
  - The (U)LIRGs have very similar line ratios as the AGN sample in Coil+ 2015.
Optical Line Diagnostics of (U)LIRGs @ $z \sim 2.3$

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Chu et al., in prep.
Summary of Results

• Improved 3-500μm SEDs for LIRGs in the local universe.
  • The FIR peak shifts towards shorter wavelength with increasing $L_{\text{IR}}$.
  • The FIR/sub-mm spectral index is roughly constant ($F \propto \nu^{4.05 \pm 0.12}$) for (U)LIRGs, $L_{\text{IR}}=10^{11}$ to $10^{12.5} L_\odot$.

• Updates to Chary & Elbaz (2001) SED libraries will be published in Chu+17.
  • there are systematic offsets in MIR/FIR colors between CE01 and C+17.
  • CE01 significantly overestimates the MIR flux above $L_{\text{IR}} \sim 10^{11.5} L_\odot$.

• Optical emission line diagnostics (BPT) of (U)LIRGs at $z \sim 2.3$ show they are more similar to X-ray selected AGN than K-band selected (i.e. MOSDEF) objects.

• Q: How compact are the $L_{\text{IR}}$ sources in high-z SMGs/ULIRGs?

Contact: jasonchu@ifa.hawaii.edu  GOALS webpage: http://goals.ipac.caltech.edu
Comparison CE01 and C+17

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