Molecular Gas and Dust in ULIRGs: SMA View

Submillimeter Array (SMA)

ALMA

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"Assembly, Gas Content and Star Formation History of Galaxies"

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Recent work on Molecular Gas and Dust in ULIRGs made with the Submillimeter Array (SMA)

**U/LIRG**: $L_{bol} > 10^{12}, 10^{11} \, L_\odot$, in mid/far-IR, mergers, S.B./AGN

**Case study on Arp 220** (=nearest ULIRG)
- Sakamoto et al. (2008, 2009)
- Matsushita et al. (2009)
- Aalto et al. (2009) → Aalto's talk (CARMA Poster by Ashley Zauderer)

**SMA Survey of U/LIRGs**
- Wilson et al. (2008)
- Iono et al. (2009)

give you idea what ALMA will do
Arp 220: Nearest ULIRG (75 Mpc), Merger

In the central kpc:
two nuclei + multi-disk system

West nucleus

Arp 220
J,H,K/HST

1" = 360 pc

HST/NICMOS. (Scoville et al. 1998)

Nuclear Disks = Major L source

based on OVRO CO(2-1), 0.5" res.
(Sakamoto et al. 1999)
Arp 220: SMA 860 μm obs.

Rotating disks & warm gas, confirmed

(Sakamoto et al. '08)
Arp 220: $L_{bol}$ of West Nucleus

Arp 220 W:

deconvolved size

Gaussian FWHM $\sim 0.15''$

uniform disk diameter $\sim 0.22''$

i.e., $d \sim 50$-80 pc

deconvolved (peak) $T_b$

$T_b = 90$-$160 \text{ K} \leq T_{dust}$

($\leq$ is due to $\tau_{dust}$)

Luminosity

$L_{bol} \approx \sigma T_d^4 \times \pi d^2$

$\geq (2$-$3) \times 10^{11} L_\odot$

Luminosity surface density

$\Sigma (L_{bol}) \geq 10^{7.6} L_\odot \text{ pc}^{-2}$

(Sakamoto et al. '08)
Arp 220: $M_{\text{dyn}}$ of West Nucleus

From CO(3-2) PV diagram

Dynamical mass

$$M_{\text{dyn}} (r \lessapprox 40\text{pc}) \sim 6 \times 10^8 M_\odot$$

(W's disk is nearly edge-on)

Luminosity-to-Mass ratio

$$L/M \approx 4 \times 10^2 \frac{L_\odot}{M_\odot}$$

(for $r \lessapprox 40\text{pc}$)

c.p.

Young, < 10 Myr, starburst can have

$$L/M \sim 1 \times 10^3 \frac{L_\odot}{M_\odot} \text{ (Starburst99).}$$

AGN can have up to

$$\frac{L_{\text{Edd}}}{M_{\text{bh}}} \sim 4 \times 10^4 \frac{L_\odot}{M_\odot}$$

Thus, both can explain the min $L/M$.

(Sakamoto et al. '08)
Arp 220: New Constraints on the Power Source

- Central 80 pc of Arp 220 W has
  \[ L_{\text{bol}} \approx 2 \times 10^{11} \, L_{\odot}, \]
  \[ \Sigma_{\text{bol}} \approx 10^{7.6} \, L_{\odot} \, \text{pc}^{-2}, \]
  \[ M_{\text{dyn}} \approx 6 \times 10^8 \, M_{\odot}, \]
  and
  \[ L/M \approx 4 \times 10^2 \, L_{\odot}/M_{\odot} \]
  \(-\) Robust estimates based on Stefan-Boltzmann and Newton's laws.

- The power sources consistent with these constraints are
  100s of $10^9 L_{\odot}$ super clusters or an equivalent starburst,
  and
  an energetically-dominant AGN(s).
  \((\text{Sakamoto et al. '08})\)

- Higher-res., higher-freq. obs. \(\Rightarrow\) tighter constraints.

High-resolution sub-mm obs.
\(\Rightarrow\) \(L_{\text{bol}}\) distribution, \(L/M\)
of deeply buried nuclei of ULIRGs
Arp 220: Comparison of $I_{\text{dust}}$ and $\Sigma_{\text{SNR}}$

If starburst-powered,

$$I_{\text{dust \ emission}} \propto \Sigma_{\text{SNR}}^{0.75-1.25},$$

for Schmidt law’s $n=1-2$

under a few simple assumptions (S08).

Arp 220E : PA~45° elongation in both $\Sigma_{\text{SNR}}$ and $I_{\text{dust}}$.

Arp 220W : different distributions

(Sakamoto et al. '08)
Arp 220 : 435 μm (690 GHz)

Matsushita et al. (2009)

1" resolution

sub-mm SED for individual components of Arp 220

→ τ_{860}: W, E ~1; outer disk ≪1; W > E.

not enough resolution for L_{bol}

(Matsushita et al. '09)
Compact HCO$^+$, extended CO(3-2).
Excitation condition limits extent of HCO$^+$.

(Sakamoto, Aalto, Wilner et al. 2009)
Arp 220 : P-Cyg profiles toward nuclei

Blueshifted Absorption + Redshifted Emission = P Cyg profile

(Sakamoto, Aalto, Wilner et al. 2009)
Arp 220: Nuclear Winds

- **Wind from each nucleus**
  \[ V_{\text{rad}} \approx 100 \text{ km/s}, \ (\text{up to} \ 500 \text{ km/s}) \]
  outflowing inner region + rotation-dominated outer region

- **Energetically plausible**
  \[ SNR \approx 3/\text{yr} \ (W), 1/\text{yr} \ (E) \]  (Lonsdale et al. 2006)
  \[ L_{\text{mech}} = 3 \times 10^{50} \text{ J/Myr} \rightarrow \Delta V = 500 \text{ km/s} \text{ for } 1 \times 10^8 M_\odot, \text{ at } 10\% \text{ eff.} \]
  \[ P_{\text{rad}} \text{ on dust may be another driver} \rightarrow \text{Thompson's talk in this session} \]

- **Outflow rate \( \approx 100 M_\odot/\text{yr} \) (w/ assumptions)**

(Sakamoto, Aalto, Wilner et al. 2009)
Arp 220: High-res. sub-mm obs.

High-resolution sub-mm obs. ➞ radial gas motion in ULIRG nuclei

Sub-mm:
- high $T_b$, dust, low $T_{ex}$, molecule ➞ line absorption
- high-J HCO+, localized around the nucleus ➞ traces kinematics near the center

High-res.:
- less contamination from non-absorbing gas.

Possible with ALMA toward many ULIRGs ➞ quenching of starburst through outflows ➞ removal of quasar shroud
SMA Survey of U/LIRGs
Wilson et al. (2008), Iono et al. (2009), ...

\[ D_L < 200 \text{ Mpc} \]
\[ \log L_{\text{FIR}} > 11.4 \]
\[ \text{dec.} > -20^\circ \]

Observed 14 (out of 39).

\[ \text{CO}(3-2), (2-1), \text{HCO}^+ (4-3), \text{and continuum} \]
\[ \sim 1 \text{kpc (1") resolution} \]

red circle = F.o.V

(Wilson et al. 2008)
Survey: CO(3-2) and $L_{\text{FIR}}$

From this linear correlation one can hope that CO(3-2) is closely related to the IR-generating activities, and is a good line to study them.

(Lono et al. 2009)

(Chung et al. 2009)
Survey: CO(3-2) in U/LIRGs

CO(3-2) res. ≈ 1 kpc

CO(3-2) is detected as ∼1 kpc peaks. 
∼50% of total is in these peaks. 
M(H₂) ∼ 10⁹ M☉

(Wilson et al. 2008)
Survey: Two Tightest Correlations

(a) \[ \log \Sigma_{H_2}^{(peak)} [M_\odot pc^{-2}] \]

\[ \log L_{\text{FIR}} [L_\odot] \]

\[ L_{\text{FIR}} \text{ v.s. } \Sigma_{H_2}^{(peak)} \]

prob. of false correlation 0.0014

(b) \[ T_{\text{dust}} [K] \]

\[ T_{\text{dust}} \text{ v.s. } \Sigma_{H_2}^{(peak)} \]

prob. of false correlation 0.0016

Gas concentration to the center (∼kpc) ⇒ More Luminosity

⇒ Warmer ISM

(Wilson et al. 2008)
Survey: Different from prev. studies

Gas concentration to the center (∼kpc) ⇒ More Luminosity

w/o increasing efficiency (=L_{IR}/M_{gas})

More in Wilson et al. (2008), Iono et al. (2009), ...

(Wilson et al. 2008)
Summary
Mol. Gas and Dust in ULIRGs: SMA

Case study with new tricks (possible w/ high-res, high-freq.)
- sub-mm continuum image, SED $\rightarrow$ distribution of $L_{\text{bol}}$, $\Sigma_{\text{bol}}$, $L_{\text{bol}}/M_{\text{dyn}}$.
- Gas outflows through absorption
  (may quench starburst and/or remove quasar shroud)
- Chemistry (e.g., line-survey, anomalous chemistry and/or excitation around AGNs)
- ...

Survey
- CO(3-2), sub-mm cont. Statistical analysis of $M_{\text{gas}}$, $\Sigma_{\text{gas}}$, $T_{\text{gas}}$, $n_{\text{gas}}$, $M_{\text{dust}}$, $T_{\text{dust}}$, $L_{\text{FIR}}$, $\Sigma_{\text{FIR}}$, etc. for star-formation law etc.
- Comparison with high-z galaxies

We can do both and more with ALMA