Luminous infrared galaxies: energetics and evolution with redshift

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Spitzer deep field
the great leap with Spitzer

- extensive deep surveys of star formation/dusty AGN/stellar masses to $z \sim 6$, covering cosmic evolution of SMGs, ULIRGs and LIRGs (to $z \sim 1.5$)
- PAH spectro-photometry to $z \sim 3$
- line spectral diagnostics in QSOs and extensive samples of (U)LIRGs
the great leap with Spitzer

and a comment:

based on the experience from IRAS/ISO we have come to call (U)LIRGs ‘starbursts’, i.e. $M_{\text{gas}}/L_{\text{FIR}} << t_{\text{Hubble}}$

as a result, (U)LIRGs are rare at $z \sim 0$
all other galaxies are called ‘normal’

I will show in this talk that this implicit conclusion may not be true anymore at high-z:

then some (U)LIRGs were ‘normal’ galaxies
infrared diagnostics of (hidden) energy sources

Veilleux et al. (QUEST): agree to within 10-20%

$\frac{[\text{Ne V}]/[\text{Ne II}]}{[\text{O IV}]/[\text{Ne II}]}$

$\frac{L(\text{MIR})}{L(\text{FIR})}$

$\frac{f_{30}}{f_{15}}$

$W_{\text{eq}}(\text{PAH})$

SED decomposition

[Seyfert (ISO)]

[Starburst (ISO)]

[QSO]

[HII-like ULIRG]

[LINER ULIRG]

[Sy2 ULIRG]

[Sy1 ULIRG]

[SEDs]

[MIR methods of quantifying the AGN contribution]

$\log \left( \frac{L(\text{MIR-BB})}{L(\text{FIR})} \right)$

$\log \left( \frac{L(\text{FIR})}{\text{[Ne II]} \text{ as reference line for } L_{\text{FIR}}} \right)$
is the Sanders et al. 1988 scenario correct?

or monsters vs. babies

ULTRALUMINOUS INFRARED GALAXIES AND THE ORIGIN OF QUASARS

D. B. Sanders, B. T. Soifer, J. H. Elias, B. F. Madore, K. Matthews,
G. Neugebauer, and N. Z. Scoville

ABSTRACT

An evolutionary connection between ultraluminous infrared galaxies and quasars is deduced from the observations of all 10 infrared galaxies with luminosities \( L(8-1000 \, \mu m) \geq 10^{12} \, L_\odot \), taken from a flux-limited sample of infrared bright galaxies. Images of the infrared galaxies show that nearly all are strongly interacting merger systems with exceptionally luminous nuclei. Millimeter-wave CO observations show that these objects typically contain \( 0.5 - 2 \times 10^{10} \, M_\odot \) of H\(_2\). Optical spectra indicate a mixture of starburst and active galactic nucleus (AGN) energy sources, both of which are apparently fueled by the tremendous reservoir of molecular gas. It is proposed that these ultraluminous infrared galaxies represent the initial, dust-enshrouded stages of quasars. Once these nuclei shed their obscuring dust, allowing the AGN to visually dominate the decaying starburst, they become optically selected quasars. The origin of quasars through the merger of molecular gas-rich spiral galaxies can account for both the increased number of high-luminosity quasars at large redshift, when the universe was smaller and gas supplies less depleted, and the observed “redshift-cutoff” of quasars which represents the epoch after galaxy formation when the first collisions occur.
is the Sanders et al. 1988 scenario correct?  

or monsters vs. babies

• ULIRGs are mostly <2:1 (major) gas-rich mergers  

• ULIRG remnants are structurally and kinematically similar to moderate mass, disky ellipticals  

• PG QSO stellar masses similar to ULIRGs  
  (Dasyra et al. 2007)

simulations: ‘QSO mode’

Springel et al. 2005, Hopkins et al. 2006
spectral diagnostic diagrams

spectral diagnostic diagrams

spectral diagnostic diagrams

AGN fractions

- $<\text{AGN}\%> \sim 37\%$ in ULIRGs, less in LINER/HII ULIRGs
- Good agreement w/ ISO results (Genzel et al. 1998)
- Strong correlations with optical spectral types and $\frac{f_{25}}{f_{60}}$
- QSOs fall along these trends

evolution of ULIRGs
two paths in the evolution?

Farrah et al. 2009
Submillimeter galaxies
Smail, Blain, Ivison et al. 1997-2002

- >1000 well detected sources > few x $10^{12} \ldots 13.3 \, L_\odot$

- volume density: $S_{850\mu m} \gtrsim 5 \, mJy \sim 10^{-5} \, h_{70}^{-3} \, Mpc^{-3}$

- make up a significant fraction of the submm background and energy release at redshift 1-4

$<z> \sim 2.2$ (Chapman et al. 2005)
but Spitzer discovered a number of $z \sim 3-4$ SMGs
Mid-IR spectra of SMGs: star formation dominated

9 SMGs: Valiante et al. 2007

24 SMGs: Menendez-Delmestre et al. 2009: >80% star formation

Mid-IR spectra of SMGs: star formation dominated

SMGs often have detectable AGNs (X-rays); these contribute \(\sim10-30\%\) to the total luminosity

Mid-IR spectra of SMGs: lower silicate extinction than local ULIRGs

star formation activity spatially extended

Menedez-Delmestre et al. 2009
Optically faint Spitzer 24 μm sources (DOGs)

Dusty star formation? Obscured AGN?

Some PAH detections, large fraction of (obscured) continua

faint at submm/mm

volume densities ~0.2x SMGs

transition objects to QSOs?

High-z ‘bump’ ULIRGs

$z \sim 2$ ULIRGs with 1.6$\mu$m stellar bump have strong PAH emission and SED reminiscent of Arp220

Desai et al. 2009

AGNs do not dominate DOG morphology

more luminous –
more compact –
more AGN dominated?

Keck/AO
Melbourne et al.
2008, 2009
HST imaging of $z \sim 1-2$ UV/optically selected (U)LIRGS

$z \sim 1$ (AEGIS)
Noeske et al. 2007
Cooper et al. 2009

$z \sim 2$ (BX/BM/BzK/DRG)
Förster Schreiber et al. 2009b
Kriek et al. 2009
high-z star forming galaxies form a SFR-M$_*$ ‘main sequence’

$SFR = 150 \, M_{*,11}^{0.8} \left( \frac{1+z}{3.2} \right)^{2.7} \, M_\odot \, yr^{-1}, \quad \eta_{SF} \geq 0.4$

Noeske et al. 2007, Daddi et al. 2007, Elbaz et al. 2007
SMGs and the formation of red spheroids

Evidence for major mergers from PdBI mm-interferometry (Tacconi et al. 2006, 2008)

relation to theory of galaxy evolution: what drives star formation over cosmic epochs?

**major & minor mergers**


**cold flows/streams:**

stellar mass assembly: ‘downsizing'

cosmological evolution: the era of LIRGs /ULIRGs

‘…at $z \geq 1$ IR-luminous galaxies …dominate star formation activity….’

Soifer, Helou & Werner 2008
is there a problem?

for Chabrier IMF at $z>1.5$:

$\text{SFR} \sim 1.5-3 \frac{dM_*}{dt}$

similar discrepancy with models

→ SFR-indicator calibration off (Herschel)
→ AGNs affecting mid-IR indicators (Daddi et al. 2007)

high-z galaxies are gas rich

is there a simple explanation?

\[ SFR = \epsilon \frac{f_{H_2} M_{\text{baryon}}}{\tau_{\text{dyn}}} = 0.24 \epsilon_{0.02} f_{0.1} M_{10}^{3/2} R_{\text{eff},4}^{-3/2} \left[ M_\odot y r^{-1} \right] \]

\[ z = 0 \quad M_{\text{max},10} = 10, f_{0.1} = 1: \quad SFR_{\text{max}} \sim 10 M_\odot y r^{-1}, L_{\text{max}} \sim 10^{11} L_\odot \text{ (MW)} \]
\[ L=10^{12}, M = 5 \times 10^{10}, SFR = 10^2: \quad R_{\text{eff}} \sim 600 \text{ pc (ULIRG merger)} \]

the same argument also suggests that \( L \sim 10^{13} \) HYLIRGs must be AGN

\[ z=2 \quad M_{\text{max},10} = 30, f_{0.1} = 5: \quad SFR_{\text{max}} \sim 150 M_\odot y r^{-1}, L_{\text{max}} \sim 10^{12.2} L_\odot \text{ (BzK)} \]
\[ L=10^{13}, M = 2 \times 10^{11}, SFR = 10^3: \quad R_{\text{eff}} \sim 800 \text{ pc (SMG merger)} \]

\[ z > 3 \quad M_{\text{max},10} = 5, f_{0.1} = 5: \quad SFR_{\text{max}} \sim 10 M_\odot y r^{-1}, L_{\text{max}} \sim 10^{11} L_\odot \text{ (LBG)} \]
AGN contribution in high-z ULIRGs

average AGN contribution to FIRB $\sim$10-16% but what about massive end?


Compton thick, dust obscured AGN contributing to $L_{24}$ in most $z$~2 massive galaxies?

the great leap with Spitzer

- Spitzer has made ground-breaking contributions to the understanding of the cosmic evolution of star formation in galaxies and the relation between AGN and star formation