The Role of Molecular Gas and Mergers in the Evolution of the Galaxy “Main Sequence”

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A new multi-wavelength study of the GOALS sample of Luminous Infrared Galaxies (LIRGs) in the local universe shows that large molecular gas fractions and galaxy interactions/mergers play a dominant role in powering these objects by fueling both intense starbursts and AGN. As the galaxy nuclei approach coalescence, AGN power reaches its peak, triggering powerful outflows, which rapidly “quench” circum-nuclear star formation as the merger remnant settles into a gas-poor, quiescent phase. Although LIRGs are relatively rare at z ~ 0, more recent deep field far-infrared surveys by Spitzer and Herschel show that they represent a substantial fraction of the massive galaxy population at higher redshift. Early analysis of these faint FIR sources suggested that LIRGs at high redshift were mainly isolated disk galaxies primarily powered in-situ by disk-wide starbursts fueled by “cold streams” of gas accretion. In this new picture, interactions, mergers, and AGN presumably played an insignificant role. This new view for high-z LIRGs was further reinforced by the apparent existence of a simple “Main Sequence” (MS) of star formation, in which the ratio of the current star-formation rate (SFR) to total stellar mass (M*) was largely independent of galaxy stellar mass. However, more recent analysis of the log(SFR) - log(M*) relation shows that this early view of the existence of a simple "MS" was incorrect, raising the strong possibility that interactions, mergers, large gas-fractions, and AGN all play a significant role in the evolution of LIRGs at all redshifts. More detailed observations with ALMA will be essential for determining the roles of both starbursts and AGN (and the role of mergers) in the evolution of LIRGs at all redshifts.

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1. A brief (30 years !) Retrospective – on the discovery of (U)LIRGs

2. New Results for Local (U)LIRGs – morphology, molecular gas fractions

3. The Nature of LIRGs at high redshift – the “Main Sequence” (MS); cold flows vs. mergers

4. New Results for the “MS” – the role of AGN “quenching”
ULTRALUMINOUS INFRARED GALAXIES AND THE ORIGIN OF QUASARS

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G. Neugebauer,1 and N. Z. Scoville4

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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.

Subject headings: galaxies: evolution — galaxies: photometry — infrared: sources — quasars
The Merger Sequence paradigm for (U)LIRGs

(a) Isolated Disk
- halo & disk grow; most stars formed
- secular growth builds bars & pseudobulges
- "Seyfert" fueling (AGN with $M_\text{bh} > 23$)
- cannot redden to the red sequence

(b) "Small Group"
- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- $M_{\text{halo}}$ still similar to before:
  dynamical friction merges the subhalos efficiently

(c) Interaction/"Merger"
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)

(d) Coalescence/(U)LIRG
- galaxies coalesce; violent relaxation in core
- gas inflows to center:
  - starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback
- but, total stellar mass formed is small

(e) "Blowout"
- BH grows rapidly; briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO:
  - recent/ongoing SF in host
  - high Eddington ratios
  - merger signatures still visible

(f) Quasar
- dust removed; now a "traditional" QSO
- host morphology difficult to observe:
  - tidal features fade rapidly
- characteristically blue/young spheroid

(g) Decay/K+A
- QSO luminosity fades rapidly
- tidal features visible only with very deep observations
- remnant redens rapidly ($\phi/A/K+A$)
- "hot halo" from feedback
- sets up quasi-static cooling

(h) "Dead" Elliptical
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to "large group" scales:
  - mergers become inefficient
- growth by "dry" mergers

Credit: P. Hopkins
Warm ULIRGs: the transition from Galaxies to Quasars 1988b
Figure 3: The total far-infrared luminosity determined from IRAS data vs CO luminosity and the total mass of H$_2$ in molecular clouds. Circles represent high luminosity IRAS galaxies which are an unbiased sample of all galaxies with $L_{\text{FIR}}$ (40-400µm) $\geq 7 \times 10^{10}$ L$_\odot$. All other symbols represent CO observations of lower luminosity bright IRAS galaxies with known and unknown selection bias (see Sanders et al. 1986a).
Figure 3: The total far-infrared luminosity determined from IRAS data vs CO luminosity and the total mass of H$_2$ in molecular clouds. Circles represent high luminosity IRAS galaxies which are an unbiased sample of all galaxies with $L_{\text{FIR}}$ (40-400µm) $\geq 7 \times 10^{10}$ L$_\odot$. All other symbols represent CO observations of lower luminosity bright IRAS galaxies with known and unknown selection bias (see Sanders et al. 1986a).
Fraction of (U)LIRGs with an AGN increases with $L_{\text{IR}}$

- Veilleux et al. 1995, 1999; Tran et al. 2001; Yuan et al. 2010

Definite AGN (orange + yellow)

- < 20% for $L_{\text{IR}} < 10^{11} \, L_\odot$
- > 50% for $L_{\text{IR}} > 10^{12.3} \, L_\odot$

Large fraction of composites (green)

- Mix of SF, AGN, shocks
- Difficult to disentangle

Yuan et al. 2010
Retrospective - LIRGs at 30

It has been 30 years since IRAS provided a complete census of Luminous Infrared Galaxies (LIRGs: $L_{\text{IR}} > 10^{11} L_\odot$) in the local universe, ~10 years since Spitzer confirmed strong evolution in the space density of LIRGs out to $z \sim 3$, and <5 years since Herschel expanded these results to even higher redshifts by providing more sensitive, and higher resolution sky maps at 70-500\( \mu \text{m} \).
Outline

1. A brief Retrospective – on the discovery of (U)LIRGs

2. New Results for Local (U)LIRGs – morphology, molecular gas fractions

3. The Nature of LIRGs at high redshift – the “Main Sequence” (MS); cold flows vs. mergers

4. New Results for the “MS” – the role of AGN “quenching”
Morphology and Molecular Gas Fraction of Local Luminous Infrared Galaxies

Dave Sanders
University of Hawaii

+ Kirsten Larson, Josh Barnes, GOALS TEAM

HST
GOALS is a sample of 203 (U)LIRGs with $L_{\text{IR}} > 10^{11} L_\odot$ and $z < 0.088$

Northern sub-sample of 65 (U)LIRGS from GOALS

Contains galaxies in every interaction stage
Multi-wavelength Photometry

- Full SEDs for all 65 galaxies
- Data from the UV (GALAX) to the IR and millimeter
- Measure accurate $L_{\text{IR}}$ and Stellar mass

X-ray, FUV, NUV, UBVI, JHK, IRAC1234, MIPS, IRAS, SCUBA

U. et al. 2012
Multi-wavelength Photometry

- Full SEDs for all 65 galaxies
- Data from the UV (GALAX) to the IR and millimeter
- Measure accurate LIR and Stellar mass

X-ray, FUV, NUV, UBVI, JHK, IRAC1234, MIPS, IRAS, SCUBA

U. et al. 2012

ALMA Workshop - IoA, U. Tokyo, 2/2016
Visual Classification Scheme

- single — s

NGC 5135

NGC 1068
Visual Classification Scheme

- minor merger: m
Visual Classification Scheme

- Major Merger: M1
Visual Classification Scheme

- Major Merger: M2
Visual Classification Scheme

- Major Merger: M3

ALMA Workshop - IoA, U. Tokyo, 2/2016
Visual Classification Scheme

- Major Merger: M4
Visual Classification Scheme

- Major Merger: M5
Infrared Luminosity

- All galaxies with $\log\left(\frac{L_{\text{IR}}}{L_\odot}\right) > 11.5$ are mergers.
- Our sample of galaxies is flux limited and incomplete in the lowest luminosity bin.
Infrared Luminosity

- All galaxies with $\log(L_{\text{IR}}/L_\odot) > 11.5$ are mergers.
- Our sample of galaxies is flux limited and incomplete in the lowest luminosity bin.
Infrared Luminosity

- Volume Corrected sample:
Infrared Luminosity

- Volume Corrected sample:
- Below \( \log(L_{\text{IR}}/L_\odot) = 11.5 \) non-interacting galaxies dominate the volume.
Nuclear Separation

![Graph showing log(L_{IR}/L_\odot) vs. Projected Nuclear Separation (kpc)].

- 75 kpc
Nuclear Separation

![Graph showing the relationship between log(LIR/L₀) and Projected Nuclear Separation (kpc).]
CO Data

- Single dish CO (1-0) line measurements
- Used a constant CO-H$_2$ conversion factor for all galaxies

\[ X_{\text{CO}} = 3.0 \times 10^{20} \text{ H}_2 \text{ cm}^{-2} (\text{K km s}^{-1})^{-1} \]
Molecular Gas

- Converted to a constant cosmology and CO-H$_2$ conversion factor for all galaxies

\[ X_{\text{CO}} = 3.0 \times 10^{20} \text{H}_2 \text{ cm}^{-2} (\text{K km s}^{-1})^{-1} \]
Molecular Gas Fraction

\[
\text{MGF} = \frac{M_{\text{H}_2}}{(M_{\text{H}_2} + M^*)}
\]
# Molecular Gas Fraction

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<td>0.14</td>
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<td>M2</td>
<td>0.20</td>
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<td>M3</td>
<td>0.33</td>
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<td>M4/5</td>
<td>0.22</td>
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![Graph showing MGF (%) vs Merger Stage]
Molecular Gas Fraction

Merger stage: M3
Infrared Morphologies

Stage

M3

NGC 5256

HST B & I

IRAC ch1

M4

Arp 220

HST B & I

IRAC ch1

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Molecular Gas Fraction

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We analyzed the visual morphologies of 65 local (U)LIRGs. All systems with \( \log (L_{\text{IR}} / L_\odot) > 11.6 \) are major mergers. It is not until merger stage M3 that we see an increase in \( \log(L_{\text{IR}} / L_\odot) \) above 12.0. The molecular gas fraction (MGF) increases during the merging process, peaking at merger stage M3 with \(< \text{MGF} > \sim 33\% \).
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A Turn-over in the Galaxy “Main Sequence”
of SFR ($L_{IR}$) at $M_\star \sim 10^{10} M_\odot$
The role of AGN and mergers in “quenching” star formation

Dave Sanders
Institute for Astronomy, Univ. of Hawaii


ALMA Workshop - IoA, U. Tokyo, 2/2016
• Star-forming galaxies seem to follow a linear relationship in $\log(SFR)/\log(M_*)$
• This relationship seems to hold at all redshifts with a dispersion of $\sim 0.3$ dex
• At higher redshifts the entire main-sequence moves up to a higher normalization
• Many studies confirm existence of “main sequence”, but lots of disagreement on slope, normalization, dispersion, etc. likely due to different IMFs, selection effects, SFR & $M_*$ indicators

Noeske+2007
Lee+13  FIR-COSMOS .... Galaxy SEDs vs. $L_{\text{IR}}$ ($z \sim 0.5 - 3.5$)

SEDs change systematically with $L_{\text{IR}}$ (as is the case locally)
Galaxies selected in the (far)-infrared do not seem to follow main-sequence relationships.
Infrared Studies of SFR/M*  

But, galaxies selected in the (far)-infrared do not seem to follow main-sequence relationships.

1.5 < z < 2.5

Rodighiero+2011

Lee+2013
A Turnover in the Main Sequence

- We measure stellar mass and SFR of over 62,000 galaxies
- SFR Ladder:
  - Herschel
  - Spitzer 24 μm
  - NRK
- Main Sequence appears to turnover at $M \sim 10^{10} M_\odot$

Lee+2015, in press
A Turnover in the Main Sequence

\[ S = S_0 - \log \left[ 1 + \left( \frac{10^M}{10^M_0} \right)^{-\gamma} \right] \]

Provides best fit to data and parameterizes:

- \( S_0 \): scaling factor
- \( M_0 \): Turnover Mass
- \( \gamma \): Low Mass Power Law slope

Lee+2015, in press
Evolution of Main Sequence

\( S_0 \): scaling factor

\( M_0 \): Turnover Mass

\( \gamma \): Low Mass Power Law slope

Redshift Evolution

Covariance

Lee+2015, in press
Summary of Lee+2015

- FIR observations are necessary to accurately constrain the SFR of luminous galaxies.
- The star-forming “main sequence” has a turnover at $M_* \sim 10^{10} M_\odot$, with possible evolution toward higher turnover masses at high redshift.
- The scaling of the star-forming main sequence rises with redshift as $\sim (1+z)^{3.2}$
- Quenching ?
Summary

• There is no single linear (log-log) “main-sequence of star-formation”, but there is an interesting correlation between galaxy SFR and $M_*$.
• The relationship between SFR and $M_*$ changes with stellar mass, with a turnover around $\log(M_*) \sim 10-10.2$ (or double power-law: $\alpha = 0.9 \rightarrow 0.2$).
• Further study needs to be done to determine the cause of this turnover and how star-forming galaxies become “quiescent”.
• The dispersion in this correlation may contain important clues for the star-formation histories of star forming galaxies.

References

• Turnover in Main Sequence – Karim+2011, Whitaker+2014, Lee+2015, Leja+2015
• Dispersion & Star Formation Histories – Kelson+2014, Abramson+2014
• Bulge Growth – Abramson+2014
Part II

The role of AGN and galaxy mergers in “quenching” $L_{\text{IR}}$ in massive galaxies

References

• AGN fraction vs. $L_{\text{IR}}$ – Kartaltepe+10, Kartaltepe+15
• Morphology, gas fraction – Hung+13
• SEDs vs. $L_{\text{IR}}$ – Lee+13,
AGN Fraction increases systematically with $L_{\text{IR}}$ (as it does locally)!

AGN Fraction at High(ER) Redshift

Kartaltepe et al. 2010a

>70% for ULIRGs
100% of HyLIRGs
5% at low $L_{\text{IR}}$
Properties of Local (U)LIRGs

- Fraction of (U)LIRGs with an AGN increases with $L_{IR}$
  - Veilleux et al. 1995, 1999; Tran et al. 2001; Yuan et al. 2010

- Definite AGN (orange + yellow)
  - < 20% for $L_{IR} < 10^{11} L_\odot$
  - > 50% for $L_{IR} > 10^{12.3} L_\odot$

- Large fraction of composites (green)
  - Mix of SF, AGN, shocks
  - Difficult to disentangle

Yuan et al. 2010
Hung+13  Herschel-COSMOS ....  Galaxy Morph in $L_{\text{IR}}$ vs. $M_*$ plane

Morphology Class
- Disk
- Spheroid
- Irregular
- Undeﬁnable

Interaction Class
- Merger
- Interacting pair
- Non-interacting pair
- Non-interacting galaxy

Table:

- 0.2 < z < 0.5
- 0.5 < z < 1.0
- 1.0 < z < 1.5
Figure 7 presents a more detailed examination of the effect of including FIR-selected galaxy samples (with well-determined $M_*$ and $L_{IR}$) in plots of SFR-$M_*$, by matching one of the specific redshift bins from Noeske et al. (2007b). The number of objects in Figure 7 is ~10x that in the original Noeske et al. sample, and in addition we have included the more accurate "SFRs" for our FIR-selected sample (red dots) and for our 24um sample (green dots), and using the NRK-method from Arnouts et al. (2013) for the optically-selected objects (blue dots).

The inclusion of FIR-selected objects seems to provide a more evident tail to high SFRs (or $L_{IR}$) at all galaxy masses, as well as suggesting a possible bimodal shape to the SFR distribution at lower galaxy masses.

Clearly these trends will be a major focus of our more complete analysis. Once we have spectra of all of our sources we can immediately replace photometric values with spectroscopic values, and carry out a more detailed comparison of different SFR indicators at all redshifts. This will become increasingly important at $z > 2$ as discussed below.

**Figure 7** SFR vs $M_*$ for COSMOS "star-forming" galaxies in the redshift range $0.7 < z < 0.85$. Galaxies are either Herschel-selected (red), Spitzer-24 selected (green) or optically selected (blue). The orange dashed line represents the "MS" taken directly from Noeske et al. (2007b). The histograms represent the SFR distribution for sources at $\log (M_*/M_{\odot}) = 10.2$ and $10.8$ in bins of $\Delta M_* = 0.2$.

### 3.2 IR-selected Galaxies: Mergers and the "Main Sequence"

**Figure 8**: Recent results from our initial study of the morphological properties of Spitzer+Herschel-selected galaxies at $z < 1.5$ in the COSMOS Field (adapted from data presented in Hung et al. 2013). (Left panel): The ratio of mergers (i.e. strongly interacting systems that will eventually merge + advanced mergers) to Non-interacting Disks in the redshift range $0.6 < z < 0.8$. The "main sequence" at $z=0.7$ (from Noeske et al. 2007) is shown as a dashed line. A strong trend of increasing fraction of merger systems with increasing infrared luminosity ($L_{IR}$) is clearly seen in all mass bins at $\log (M_*/M_{\odot}) > 10.0$. (Right panel): Sample HST-ACS I-band images of the different morphological classes.
Summary 3

- The “main-sequence of star-formation” provides an interesting correlation between galaxy $L_{IR}$ and $M_*$
- The relationship between $L_{IR}$ and $M_*$ changes with stellar mass, with a turnover around $\log(M_*/M_{\text{sun}}) \sim 10-10.2$
- Mergers and powerful AGN drive the observed “quenching” for massive galaxies
- The dispersion in this correlation contains clues for the star-formation and AGN growth histories of molecular gas-rich galaxies
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Quenching star formation: insights from the local main sequence

S. K. Leslie\textsuperscript{1*}, L. J. Kewley\textsuperscript{1}, D. B. Sanders\textsuperscript{2}, N. Lee\textsuperscript{2}

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\textsuperscript{2}Institute for Astronomy, 2680 Woodlawn Dr., Honolulu, HI, 96822, USA

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{SFR vs. $M_*$.}
\end{figure}

Pure SF

log(SFR) vs. log($M_*$)
Quenching star formation: insights from the local main sequence

S. K. Leslie\textsuperscript{1*}, L. J. Kewley\textsuperscript{1}, D. B. Sanders\textsuperscript{2}, N. Lee\textsuperscript{2}

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![Diagram of the main sequence with annotations](image)

"LIRGs"
Quenching star formation: insights from the local main sequence

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**Figure 1.** SFR as a function of stellar mass for each class of galaxies. Stellar mass and SFRs are in units of \(M_\odot\) and \(M_\odot\,\text{yr}^{-1}\) respectively throughout this work. The top-left to bottom-right panels include galaxies classified as purely star-forming, composite, Seyfert 2, LINER, or Ambiguous, and the final panel contains all classes together. A black dashed line in each panel represents the local MS relation for blue SDSS galaxies determined by Elbaz et al. (2007). Contours and colours represent the number density of galaxies in a single class only. Dividing the SFR-\(M_\star\) space into 150x150 bins, contours are drawn at 10, 30, and 60% of the maximum number density. The blue contours of the star-forming galaxies are included in all panels to indicate the location of the star forming MS. Contours from previous panels are also shown in the final panel, which displays the MS of all galaxies.
McPartland, Sanders et al. 2016, in prep.

“Quenching” and Morphology (B/T)

Fig. 2.— Top: Figure 1 of Leslie et al. (2016) showing a two-dimensional histogram of star-formation rate versus mass for SDSS galaxies with varying AGN contribution as determined by optical emission line ratios. Bottom Median bulge to total ratio in bins of star-formation rate versus mass from McPartland et al. (in preparation) using a similar sample as Leslie et al. Note the increase in bulge fraction along the high SFR limit of star-forming galaxies (left) and with the progression of AGN stages (3 rightmost panels).
McPartland, Sanders et al. 2016, in prep.

“Quenching” and Morphology (B/T)

Fig. 2.— Same as Fig. 1 for Bulge-to-Total.
Fig. 6.— Same as Fig. 1 for the $q$ parameter of Condon+1991. Note that cells with $q > 2.8$ are fixed to dark red and that cells with $q < 1$ are fixed to dark blue.

“Quenching” and FIR/Radio $(q)$

McPartland, Sanders et al. 2016, in prep.
1. Galaxy Interactions and mergers play a major role in the evolution of galaxies at all redshifts

2. Gas-rich galaxy mergers play a dominant role in fueling luminous Nuclear Starbursts and building Massive Black Holes at all redshifts

3. Molecular gas-rich mergers play a major role in the transformation of massive galaxies – from blue spirals to red ellipticals

4. ALMA (< 0.1” res) will be critical for understanding the role of molecular gas in fueling both Starbursts and AGN

5. ALMA will be critical for understanding the role of feedback (stellar and AGN winds) in galaxy “quenching”