Fingerprinting (ultra)luminous infrared galaxies

Paul van der Werf
Leiden Observatory
Institute for Astronomy
University of Edinburgh

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"Simple people who think that they can learn astronomy by only looking at the stars, without knowledge of mathematics, will in a future life become birds."

(Plato, Τιμαίος)

"Imaging is for the man who cannot do spectroscopy."

(Origin unknown)
Credits

Kate Isaak (ESTEC)
Padelis Papadopoulos (Bonn University)
Rowin Meijerink (Leiden Observatory)
Edo Loenen (Leiden Observatory)
Eduardo González-Alfonso (Henares)
Marco Spaans (Kapteyn Astronomical Institute)
Axel Weiss (MPI für Radioastronomie)
Francesco Costagliola (Onsala)
Susanne Aalto (Onsala)
Outline

- Molecular gas in (U)LIRGs ($L_{IR} > 10^{11(12)} L_{\odot}$)
- The CO rotational ladder as a PDR/XDR diagnostic
- What do H$_2$O and other lines tell us?
- Outlook
THE INFRARED-GALAXY PHENOMENON

FRANK J. LOW

Department of Space Science, Rice University, Houston, Texas, and Lunar and Planetary Laboratory, University of Arizona, Tucson

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ABSTRACT

An ensemble of identical infrared sources, called irtrons, radiates the quiescent infrared continuum now found to characterize the nuclei of all galaxies. Continuous creation of matter and antimatter within the irtrons releases energies greater than $10^{42}$ ergs. The observed infrared continuum results from coherent synchrotron decay of electrons and positrons produced by annihilation. The observed infrared luminosities form an evolutionary sequence beginning with QSOs, extending to Seyfert galaxies and exploding galaxies, and ending with large spirals like our own.
ULIRGs \( (L_{\text{IR}} > 10^{12} L_{\odot}) \)

Interacting Galaxies

Hubble Space Telescope • ACS/WFC • WFPC2

(Evans et al.)
Molecular gas in ULIRGs

- CO 1–0 reveals large gas masses, concentrated in compact structures (disks or rings), typically < 1 kpc in radius (Downes, Solomon, Radford, Scoville,…)

- X-factor converting CO luminosity into H$_2$ mass is subject of endless debate, since

\[
X \propto \frac{\sqrt{n}}{T_b}
\]

- In ULIRGs a factor of 5 below “normal” is often adopted (Downes, Solomon, et al). Uncertain!

- Higher CO lines trace gas that is both warm and dense. Resulting H$_2$ masses (e.g., for high-z galaxies) are then even more uncertain.
(U)LIRGs from low to high \(z\)

- **Downsizing:**
  Looking back towards higher redshifts, star formation occurs in increasingly more luminous (dusty) galaxies.

- Can luminous high-\(z\) galaxies be understood using the same tools and models as at low \(z\)?

*(Le Floc’h et al. 2005)*

_Fingerprinting Ultraluminous Infrared Galaxies_
ISM in luminous high-z galaxies

- Even in ALMA era, limited spatial resolution on high-z galaxies.
- For unresolved galaxies, multi-line spectroscopy will be a key diagnostic

(Danielson et al. 2010)

(Weiß et al. 2007)
Warning: may contain...

- quiescent molecular (and atomic) gas
- star-forming molecular gas (PDRs)
- AGN (X-ray) excited gas (XDRs)
- cosmic ray heated gas
- shocks
- mechanically (dissipation of turbulence) heated gas
- warm very obscured gas (hot cores)

See talk by Meijerink (PDR/XDR)
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PDRs vs. XDRs

Four differences:

- X-rays penetrate much larger column densities than UV photons
- Gas heating efficiency in XDRs is ≈10–50%, compared to <1% in PDRs
- Dust heating much more efficient in PDRs than in XDRs
- High ionization levels in XDRs drive ion-molecule chemistry over large column density
PDRs vs. XDRs: CO lines

- XDRs produce larger column densities of warmer gas
- Identical incident energy densities give very different CO spectra
- Very high J CO lines are excellent XDR tracers
- Need good coverage of CO ladder

(Spaans & Meijerink 2008)
Introducing HerCULES

Herschel
Comprehensive
(U)LIRG
Emission
Survey

Open Time Key
Program on the
Herschel satellite
HerCULES in a nutshell

- HerCULES will uniformly and statistically measure the neutral gas cooling lines in a flux-limited sample of 29 (U)LIRGs.

- Sample:
  - all IRAS RBGS ULIRGs with $S_{60} > 12.19$ Jy (6 sources)
  - all IRAS RBGS LIRGs with $S_{60} > 16.8$ Jy (23 sources)

- Observations:
  - SPIRE/FTS full high-resolution scans: 200 to 670 μm at $R \approx 600$, covering CO 4–3 to 13–12 and [CI] + any other bright lines
  - PACS line scans of [CII] and both [OI] lines
  - All targets observed to same (expected) S/N
  - Extended sources observed at several positions
Who is HerCULES?

Paul van der Werf (Leiden; PI)  
Susanne Aalto (Onsala)  
Lee Armus (Spitzer SC)  
Vassilis Charmandaris (Crete)  
Kalliopi Dasyra (CEA)  
Aaron Evans (Charlottesville)  
Jackie Fischer (NRL)  
Yu Gao (Purple Mountain)  
Eduardo González-Alfonso (Henares)  
Thomas Greve (Copenhagen)  
Rolf Güsten (MPIfR)  
Andy Harris (U Maryland)  
Chris Henkel (MPIfR)  
Kate Isaak (ESA)  
Frank Israel (Leiden)  
Carsten Kramer (IRAM)  
Edo Loenen (Leiden)  
Steve Lord (NASA Herschel SC)  

Jesus Martín-Pintado (Madrid)  
Joe Mazzarella (IPAC)  
Rowin Meijerink (Leiden)  
David Naylor (Lethbridge)  
Padelis Papadopoulos (Bonn)  
Adam Rykala (Cardiff)  
Dave Sanders (U Hawaii)  
Giorgio Savini (Cardiff/UCL)  
Howard Smith (CfA)  
Marco Spaans (Groningen)  
Luigi Spinoglio (Rome)  
Gordon Stacey (Cornell)  
Sylvain Veilleux (U Maryland)  
Cat Vlahakis (Leiden/Santiago)  
Fabian Walter (MPIA)  
Axel Weiß (MPIfR)  
Martina Wiedner (Paris)  
Manolis Xilouris (Athens)
## HerCULES sample

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Mrk231

- At \( z = 0.042 \), one of the closest QSOs (\( D_L = 192 \) Mpc)
- With \( L_{\text{IR}} = 4 \cdot 10^{12} L_\odot \), the most luminous ULIRG in the IRAS Revised bright Galaxy Sample
- “Warm” infrared colours
- Star-forming disk (\( \sim 500 \) pc radius) + absorbed X-ray nucleus
- Face-on molecular disk, \( M_{\text{H}_2} \sim 5 \cdot 10^9 M_\odot \)

HST/ACS
(Evans et al., 2008)
Mrk231

SPIRE FTS

(Van der Werf et al., 2010)

Fingerprinting Ultraluminous Infrared Galaxies
CO excitation

Fingerprinting Ultraluminous Infrared Galaxies
CO excitation

3 PDRs

6.4:1:0.03

Solar luminosities

Upper J Level

- n=10^{6.5}, G_0=10^{5.0}
- n=10^{3.5}, G_0=10^{2.0}
- n=10^{5.0}, G_0=10^{3.5}
High-J lines: PDR or XDR?

- High-J CO lines can also be produced by PDR with $n=10^{6.5} \text{ cm}^{-3}$ and $G_0=10^5$, containing half the molecular gas mass.

- Does this work?
  - $G_0=10^5$ only out to 0.3 pc from O5 star; then we must have half of the molecular gas and dust in 0.7% of volume.
  - With $G_0=10^5$, 50% of the dust mass would be at 170K, which is ruled out by the Spectral Energy Distribution.
  - $[\text{OH}^+]$ and $[\text{H}_2\text{O}^+] > 10^{-9}$ in dense gas requires efficient and penetrative source of ionization; PDR abundances factor 100—1000 lower.

Only XDR model works!
PDR/XDR model

- **PDR 1:**
  - $n=10^{3.5}$, $G_0=10^2$, $R\sim500\text{pc}$
  - Large scale molecular gas
  - $\to$ Low-$J$ CO, low H$_2$O lines

- **PDR 2:**
  - $n=10^5$, $G_0=10^{3.5}$
  - Small, dense SF clumps
  - $\to$ mid-$J$ CO lines

- **XDR:**
  - $n=10^{4.2}$, $F_X=28$, $R\sim150\text{pc}$
  - Circumnuclear XDR disk
  - $\to$ High-$J$ CO, OH$^+$, H$_2$O$^+$, high H$_2$O lines

Fingerprinting Ultraluminous Infrared Galaxies
The nearest starburst galaxy: M82

- At $D = 3.9$ Mpc, one of the closest starburst galaxies
- With $L_{\text{IR}} = 3 \cdot 10^{10} L_{\odot}$, a very moderate starburst
- “Cool” infrared colours
CO ladder of M82: SPIRE-FTS

- FTS spectrum dominated by CO lines
- No H$_2$O lines detected
- CO fluxes drop towards high $J$

(Fingerprinting Ultraluminous Infrared Galaxies (Panuzzo et al., 2010))
HIFI observations of M82

- HIFI spectra reveal multiple components with different excitation
  
  (Loenen et al., 2010)

(CO 6–5, JCMT)
CO ladder of M82

- CO ladder drops at high $J$

- Combination of PDRs accounts for both the $^{12}$CO and the $^{13}$CO lines

- Highest excitation component can be identified in line profiles

Fingerprinting Ultraluminous Infrared Galaxies

(Loenen et al., 2010)
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H$_2$O lines in M82

- Complex and diverse line profiles
- Absorption depth $\Rightarrow$ large covering factor

(Weiß et al., 2010)
Mrk231
SPIRE FTS: H$_2$O emission lines


- **Low lines: extended component**
- **High lines: compact component**
- **Radiative pumping dominates**

(González-Alfonso et al., 2010)
Tracers of UV-shielded warm gas

- Hot core molecules (cf., Orion) trace warm, dense gas that is shielded from UV-radiation
- Regions of extreme obscuration?
  - E.g., H$_2$O, HC$_3$N

(Costagliola et al., submitted)
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1) New Herschel data

- CO, H$_2$O, [C I], [N II], CH$^+$ similar to Mrk231
- OH$^+$ emission detected but no H$_2$O$^+$
- A few “new” lines
2) Connection with high redshift

- Multi-line approach is a key diagnostic for ALMA

- High-$J$ CO lines probe high-$z$ black hole formation
  (e.g., Spaans & Meijerink 2008, Schleicher et al., 2010)

- $\text{H}_2\text{O}$, $\text{OH}^+$, $\text{H}_2\text{O}^+$ measures local infrared radiation field and ionizing radiation (follow-up with IRAM/PdBI at $z=3.9$ proposed)

- Can we derive $f_{\text{Edd}}M_{\text{BH}}$ using modeling of the CO ladder?
3) Radiative feedback

In progress: more detailed model, Including XDR and PDRs, taking into account all data

⇒ measure radiative feedback by deriving the X-ray luminosity deposited in the circumnuclear medium

⇒ derive mechanical feedback due to radiation pressure

⇒ Can this drive the molecular outflows observed from Mrk231?

See also Fischer talk

(Fischer et al., 2010)

(Feruglio et al., 2010)
CO ladder provides a diagnostic to separate star formation from AGN power in dusty galaxies, but accurate measurements of the “complete” CO ladder are needed.

CO can be an important cooling channel in luminous galaxies

H$_2$O lines turn out to be radiatively excited and therefore probe the local infrared radiation field

H$_2$O lines do not appear to be an important coolant for the warm molecular ISM

Prospects for probing radiative and mechanical feedback using the CO ladder and H$_2$O lines are being explored

H$_2$O$^+$, OH$^+$: local radiation environment (X-rays, cosmic rays)

All of these will be tools for the high-z universe with ALMA