Modeling the dust emission in (U)LIRGs:

Studying the molecular gas heating mechanisms*

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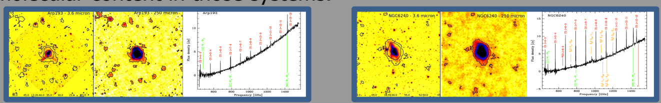
The Sample

Our sample consists of 29 galaxies all observed within the framework of the Herschel Comprehensive (U)LIRG Emission Survey (HerCULES; van der Werf et al. 2010, A&A, 518, 42), an open time Key Project on the ESA *Herschel Space Observatory.* All galaxies were observed with the SPIRE and PACS instruments (in both imaging and spectroscopic mode) providing a comprehensive inventory of the dust and the molecular content in those systems.



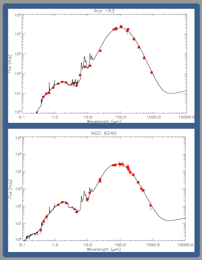
Arp 193 (left) and NGC 6240 (right). The maps on the leftmost side are the 3.6 μm Spitzer-IRAC observations with the 250 μm Herschel-SPIRE emission (middle panels) overplotted as contours. The rightmost plots are the Spectral Line Energy Distributions (SLEDS) observed by the SPIRE-FTS instrument.

Modeling of the SEDs

After careful compilation of panchromatic continuum data, we modeled the Spectral Energy Distributions (SEDs) of the galaxies in our sample using CIGALE (Noll et al. 2009, A&A, 507, 1793).

This code employs dust-attenuated stellar population models to fit the far-UV/optical SED and ensures that the dust-absorbed UV photons are re-emitted in the far-IR.

The far-continuum is modeled using the templates by Dale & Helou (2002, ApJ, 576, 159) and Chary & Elbaz (2001, ApJ, 556, 562)



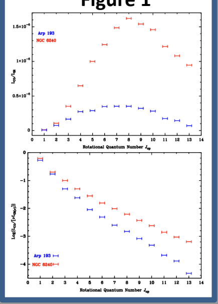
SEDs of Arp 193 (top) and NGC 6240 (bottom) modeled by the CIGALE code.

Molecular gas heating mechanisms: NGC 6240 and Arp 193 as case studies

We used the SPIRE/FTS instrument aboard the *Herschel Space Observatory* to obtain the Spectral Line Energy Distributions (SLEDs) of CO from J=4–3 up to J=13–12 of Arp 193 and NGC 6240, two classical merger/starbursts selected from our molecular line survey of local Luminous Infrared Galaxies (LIRGs: $L_{IR} \geq 10^{11}\ L_{\odot}$). The high-J CO SLEDs are then combined with our ground-based low-J CO, ^{13}CO, HCN, HCO^+ and CS line data as well as dust emission SEDs, and used to obtain an inventory of the ISM components and their thermal and dynamical states.

CO SLEDs of Arp 193 and NGC 6240. The two IR-normalized CO SLEDs markedly deviate from J=4–3 onwards with NGC 6240 having a highly excited SLED with large line/continuum ratios up to J=13–12 while Arp 193 has a significantly lower global high-J CO excitation (and line/continuum ratios) despite being one of the three most intense starbursts in the local Universe (see Figure 1).

Figure 1



The dense gas phase: the HCN, HCO^+ and CS lines.

We start the radiative transfer modeling with the HCN, HCO^+ lines since (HCN/HCO^+) - rich gas is where the minimal high-J CO SLEDs in galaxies are set. We used the public Large Velocity Gradient (LVG) code RADEX (van der Tak et al. 2007, A&A, 468, 627) to map the [n, Tkin, Kvir] parameter space compatible with the heavy rotor lines available for NGC 6240 and Arp 193. In Figure 2 we show the probability density functions (pdfs) for [n,Tkin] as constrained by the HCN line ratios. For NGC 6240 where several HCO^+lines are also available, a nearly identical solution space is recovered. The HCN SLEDs that correspond to the solution space shown in Figure 2 are plotted in Figure 3, along with those for the HCO^+ and CS lines available for NGC 6240.

Figure 2

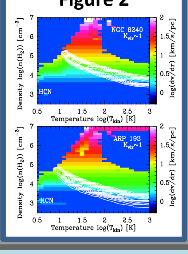
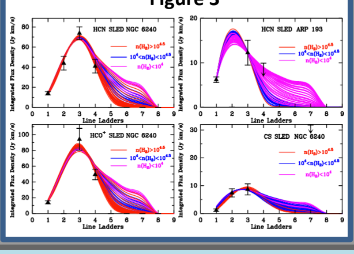
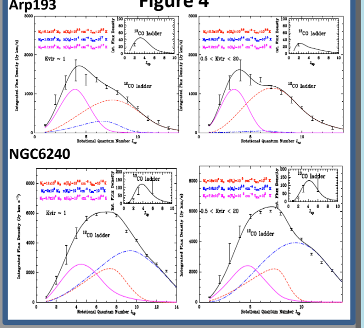


Figure 3



Modeling the CO SLEDs of Arp 193 and NGC 6240. A massive dense and warm HCN-rich non-PDR component in merger/starbursts is bound to significantly contribute to their high-J CO line luminosities. We use this to model the complete CO SLEDs of NGC 6240 and Arp 193 from J=1–0 up to J=13–12 using the LVG solution space defined solely by the HCN line ratios (Figures 2,3). The dense components (A) and (B) (red, blue dotted lines in Figure 4) are drawn from the LVG solution space compatible with the HCN, HCO^+, and CS line ratios measured for this system (see Figs 2 and 3), while a lower-density component (C) (pink in Figure 4) is needed to account for the low-J CO line emission.

Figure 4



Conclusions:

- In Arp 193, only ~(5–15)% of its molecular gas mass reservoir is at densities $n \geq 10^4\ cm^{-3}$ (i.e. the primary star formation "fuel"), while in NGC 6240 this rises to ~(70–90)%, as expected for a merger/starburst. Intense SF feedback, with Arp 193 "caught" during a short-timescale gas-(dispersal/consumption) maximum of its duty cycle, may be the reason behind this disparity.
- In both galaxies the dense gas responsible for their luminous heavy rotor lines can account also for their high-J CO SLEDs from J=4–3, 5–4 up to J=13–12. For NGC 6240 most of the molecular gas is in states irreducible to self-gravitating and photo-electrical heated clouds while this is also the case for the warmest gas in Arp 193.
- The strong turbulence and/or the high CR energy densities expected in compact merger/starbursts can volumetrically heat large amounts of dense molecular gas to high temperatures without destroying the more complex heavy rotor molecules like HCN as far-UV light from PDRs would readily do. Such non-dissociative yet strong gas heating mechanisms can then maintain large amounts of dense molecular gas in merger/starbursts with luminous high-J CO and heavy rotor molecular SLEDs.
- We deduce [CO/^{13}CO] abundances of ≥150 (Arp 193) and up to ~300-500 (NGC 6240), much higher than anywhere in the Milky Way. A top-heavy stellar IMF can enrich the bulk of the molecular gas with such a high [CO/^{13}CO] abundances. Measuring isotope ratios of atoms like C, N, and S using a multiplicity of isotopologues and rotational transitions may allow ALMA to probe the stellar IMF in galaxies where there strong reasons it may be different, but also where direct probing using starlight is impossible because of the high extinctions.