A Survey of the Molecular ISM of Nearby Galaxies using Herschel

The Herschel SPIRE Fourier Transform Spectrometer (FTS) has allowed us to observe the ^{12}CO J=4-3 to J=13-12 lines of the interstellar medium (ISM) from nearby galaxies. Such lines offer an opportunity to study warmer, more luminous molecular gas than that traced by ^{12}CO J=1-0. Here we present a survey of 17 infrared-luminous galaxy systems (21 pointings) observed by the FTS. Using simultaneous LVG models, we found the CO is emitted from a low-pressure/high-mass component traced by the low-J lines and a high-pressure/low-mass component which dominates the luminosity. This second component's pressure is comparable to that of the Sgr B2 molecular cloud, but non-resolved galaxy observations are not sensitive to the even higher-pressure molecular cores embedded within. There is a shallow correlation between L_{FIR} (SFR) and the warm gas pressure, but not the cool gas pressure. We provide additional comparisons to high-redshift galaxies, discuss the systematic effects of two-component modeling, and the errors that are introduced when using one-component LVG models. We will also preview the application of this methodology to a much larger sample of galaxies observed by the SPIRE-FTS.

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Molecular Gas Conditions

Using simultaneous LVG models, we fit the spectral line energy distributions of CO from J=1-0 to J=13-12 (Fig. 1) as the sum of two components of gas, each described by a temperature, density, column density, and area filling factor. The cooler, low-pressure component dominates the mass and the emission of the lowest-J lines, while the warmer, high-pressure gas dominates the total luminosity, emitted in higher-J lines. Some average properties are shown in Table 1. The temperatures derived from CO, dust, and [CI] are not correlated, though masses from CO and [CI] are.

Table 1: Average Properties

Quantity	Sample Average
L_{CO}/L_{FIR}	4 x 10^{-4}
Warm/Cool Pressure	60 ± 30
Warm/Cool Mass	0.11± 0.02
Warm/Cool Luminosity	15.6 ± 2.7
Gas/Dust Mass	76 to 42 over L_{FIR} range
$\alpha_{CO} = M_{gas}/L'_{CO1-0}$ [$M_\odot$(K km s^{-1} $pc^2)^{-1}$]	0.7 ± 0.5
$X_{CI/H2}$	$1^{+2}_{-0.7}$ x 10^{-4}

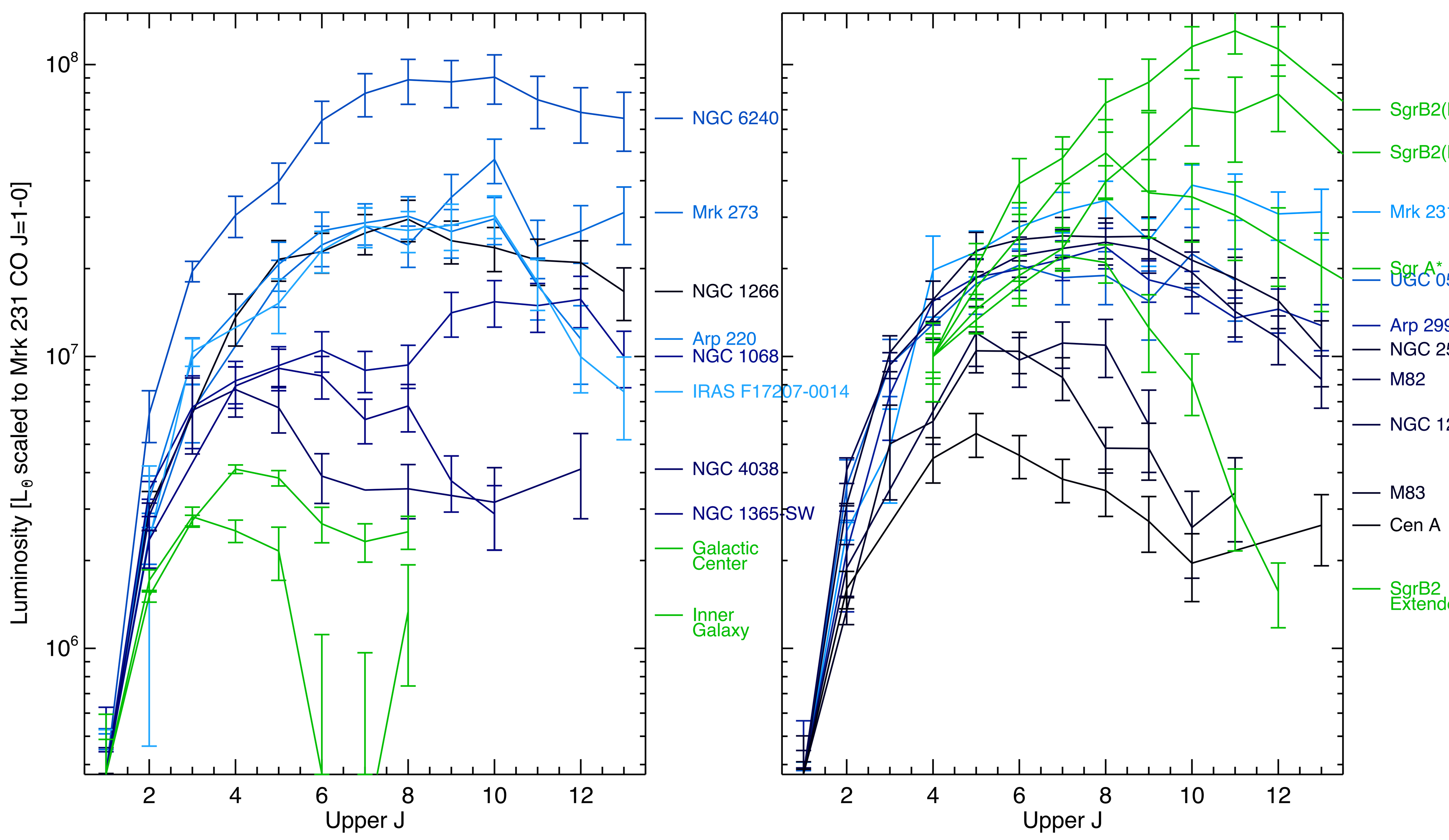

Figure 1: CO Spectral Line Energy Distributions (SLEDs). All J=1→0 luminosities are scaled to match that of Mrk 231 (3.7 ×10^5 $L_\odot$. SLEDs are colored to indicate increasing L_{FIR} with increasing lightness, and not corrected for dust extinction. Placement in the left or right panel is for clarity only. On the left panel, the SLEDs of the Galactic center (l/l < 2. 5) and the Inner Galaxy (2. 5 < l/l < 32. 5), also normalized, are shown in green for comparison (Fixsen et al. 1999). On the right panel (scaled to J=4→3 to 10^7 $L_\odot$), we show the SLEDs of two star-forming cores and the extended envelope of Sgr B2 (Etxaluze et al. 2013) and that of Sgr A* (Goicoechea et al. 2013).

Table 2: The Sample

Galaxy	D_L (Mpc)	Log L_{FIR} ($L_\odot$)
Mrk 231	188	12.4
IRAS F17207-0014	190	12.3
IRAS 09022-3615	262	12.2
Arp 220	81	12.1
Mrk 273	168	12.1
UGC 05101	176	12.0
NGC 6240	108	11.8
Arp 299-A, B, C	49	11.7
NGC 1068	16	11.4
NGC1365-SW, NE	21	11.1
NGC 4038, Overlap	23	10.9
M82	4	10.8
NGC 1222	35	10.7
M83	6	10.5
NGC 253	3	10.5
NGC 1266	31	10.4
Cen A	4	9.9

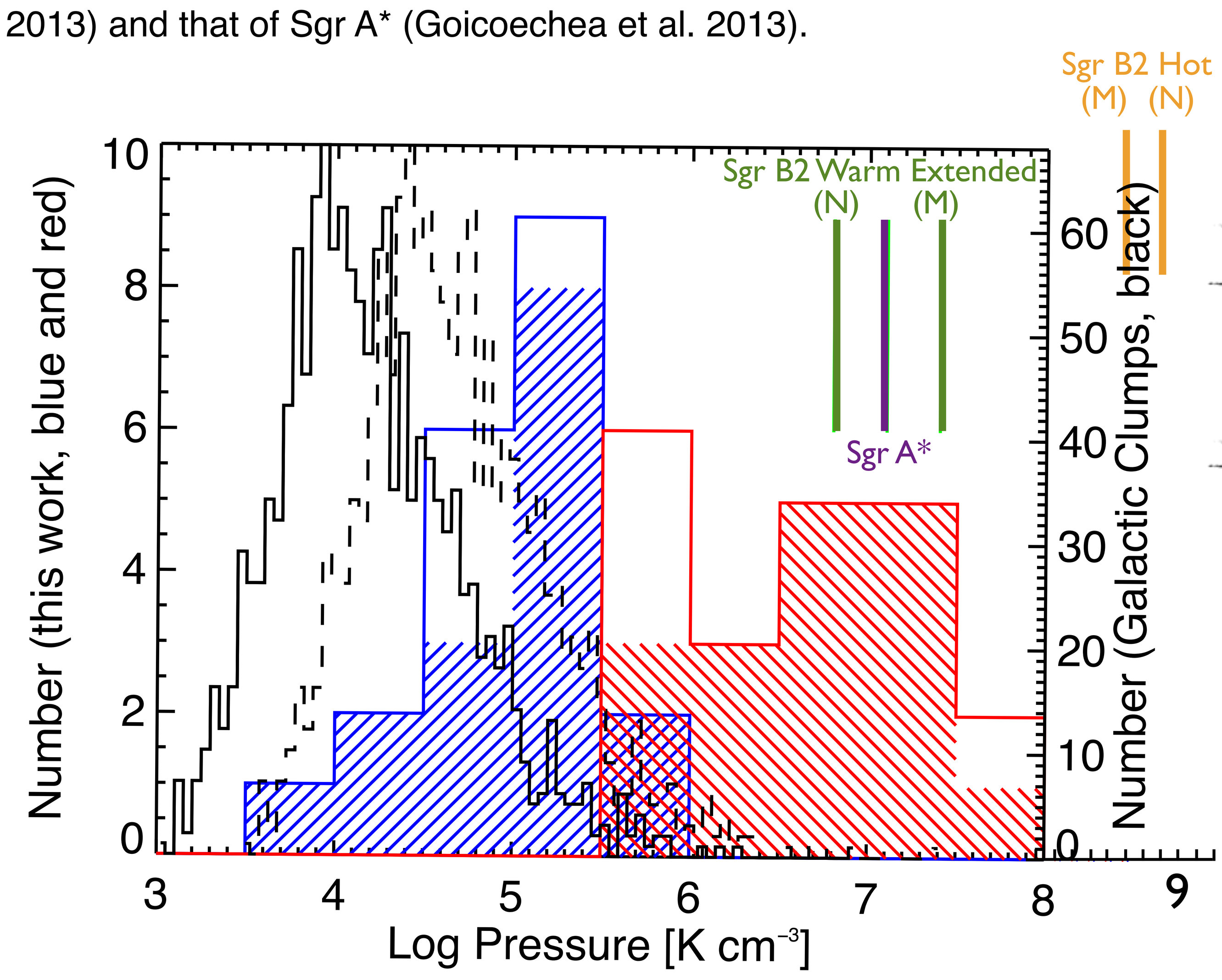

Figure 2: Gas Pressure Histograms. Left axis, blue (upward slant) = cold, red (downward slant) = warm component of this sample. Duplicate galaxy pointings are not filled in by lines. Right axis, black solid (dashed) histogram = Galactic molecular clumps using densities determined by the BGPS (Ellsworth-Bowers et al., in prep), at a temperature of 10 (30) K.

Systematic Effects of 2-Component Modeling

- Prior to Herschel, only the first few CO lines were observable; models using only those lines overestimate the gas pressure by 0.5 dex, and do not measure the total CO luminosity.
- One (non-LTE) component is not sufficient.
- However, three components do not fit the SLEDs any better than two components.
- There is likely a gradient of conditions present. Our two-components are a simple data-driven description of the galaxy-integrated distributions of warm/cool gas. Power law distributions of physical conditions may also be able to describe the SLEDs.
- Observations missing the lowest two lines (e.g. high-z) will likely underestimate the total mass by factors of ~ 2 to 8.
- These uniformly reduced CO SLEDs, of different types of galaxies, can be compared to high-z or galaxy evolution models.

Comparison to Galactic Regions

- The warm component pressure in this sample (red, Figure 2) is higher than Galactic clumps (black). It may be slightly correlated with L_{FIR}; there is not similar evidence for the cold component.
- CO J=4-3 to J=11-10 SLEDs of Sgr B2 (N) and (M) were described by 2 components, warm (green lines) and hot (orange lines): the pressures for our warm component are consistent with those of the Sgr B2 extended molecular cloud emission, and lower than that of the hot components.
- Examining the total integrated flux of the Sgr B2 SPIRE FTS map, as one would measure if it were a distant point-source, the resulting SLED is similar to that of the Sgr B2 molecular cloud, not the cores.
- Such regions, though bright in high-J lines, are "diluted" in Galaxy-integrated SLEDs.

A Larger Sample

- The Herschel SPIRE FTS observed 287 galaxies.
- Initial line fitting indicates > 100 of these contain at least 8 of the 13 strong lines (CO, [CI], [NII]) in the FTS band.
- At least 78 have 2 of the 3 lowest-J CO lines available in the literature, necessary for 2-component modeling.
- Awarded ALMA follow-up will better discern the spatial distribution of gas pressures.

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