Diagnostic Emission Lines in the Far-Infrared

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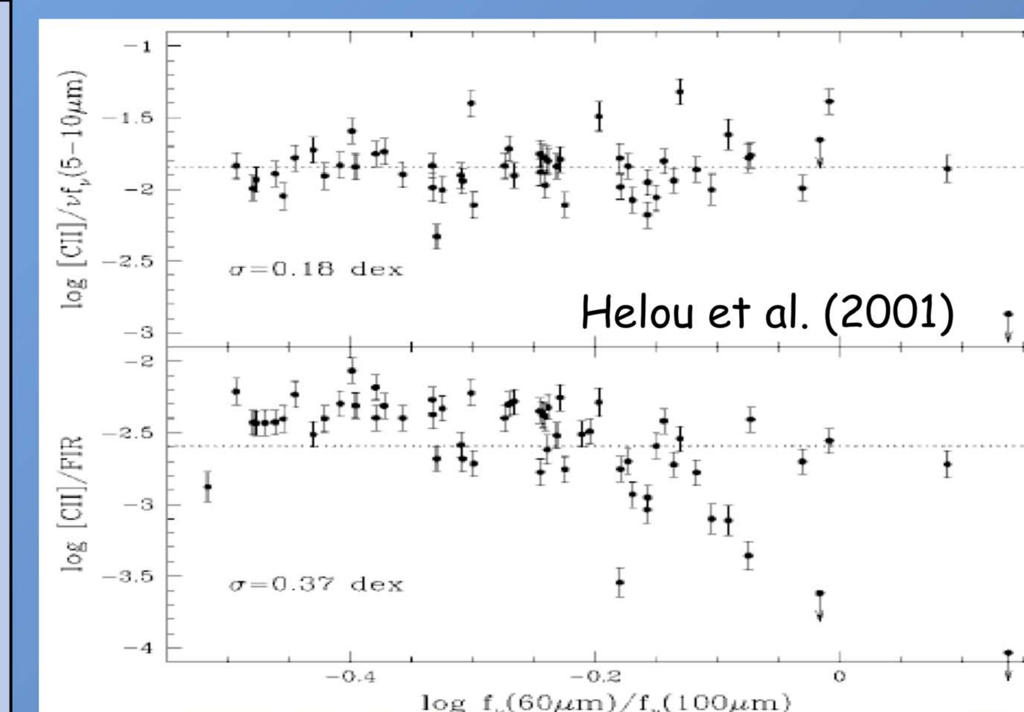
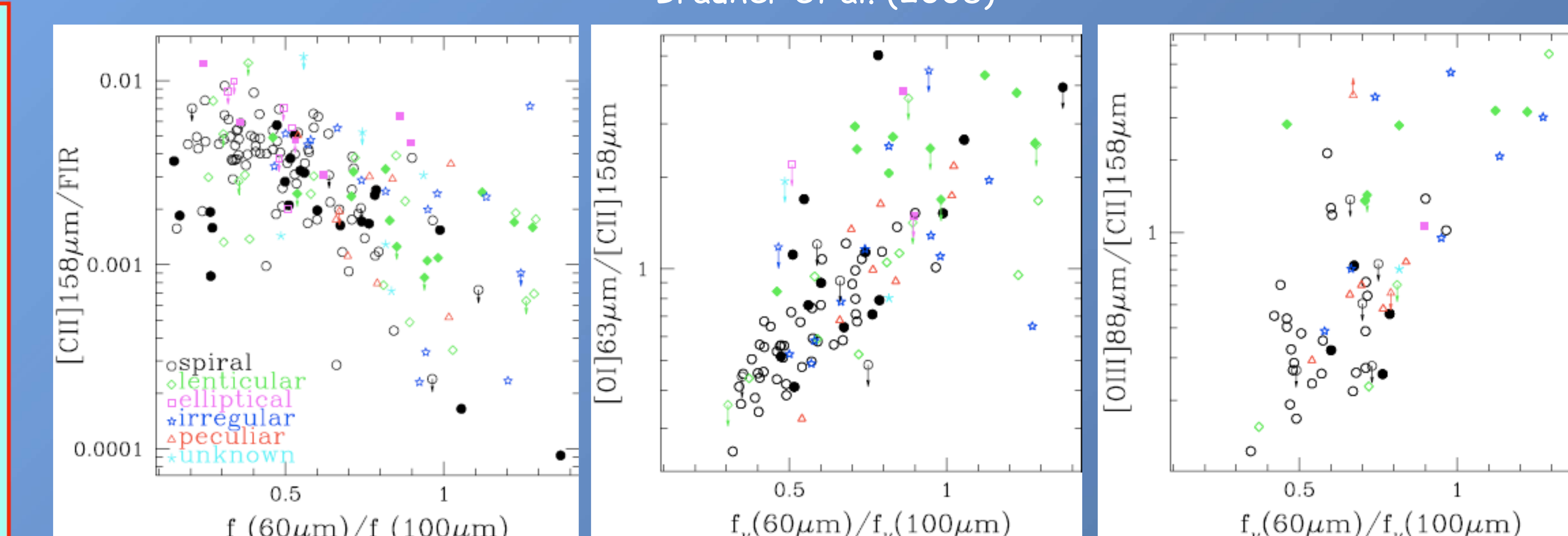
Abstract

Measurements of the PAH features and high-ionization fine-structure lines in the mid-infrared with Spitzer have been used successfully to probe the dust properties and power sources in normal star-forming galaxies at low-redshift, and the most luminous sources at $1 < z < 3$. At the highest redshifts, these lines enter the far-infrared, which is also home to critical diagnostics of the neutral interstellar medium. In particular, the [CII] and [OI] emission lines are the most important coolants of the warm, neutral ISM in galaxies. Measuring the cooling lines is critical for establishing the energy budget of galaxies, and therefore setting limits on the buildup of stars and central AGN. A large, cooled, far-infrared telescope in space is necessary to measure the diagnostic emission features from samples of rapidly evolving, normal galaxies at high redshift, extending the Spitzer results to high-redshifts and accessing the FIR diagnostics pioneered with ISO.



Brauher et al. (2008)



MIR Diagnostic Lines

- The [NeV] 14.3, 24.3 μm and [OIV] 25.9 μm fine-structure lines are effective indicators of the dominant power source (AGN or SB) in dusty galaxies, typically used in conjunction with the EQW of one or more PAH features (e.g., 6.2 μm).

- The ionization state and density of the gas can be measured via ratios of the [NeIII] 15.5 μm, [NeII] 12.8 μm, [SiII] 34.8 μm and [SIII] 18.7, 33.5 μm lines. Line profiles measure of the dynamics of the ionized gas.

FIR Cooling Lines

- The [CII] 157.7μm line ($\Delta E/k = 91$ K) is the primary coolant of the warm, neutral ISM, although it also arises in HII regions. The [OI] 63.2 μm ($\Delta E/k = 228$ K, $n_{crit} = 5\times10^{5}$ cm^{-3}) and [OIII] 88 μm lines become more important than [CII] at higher temperatures and densities.

- Photoelectrons ejected from dust grains dominate the heating of the neutral gas. The efficiency (gas heating / grain heating rate) is typically 0.1-1% (observed as the ratio of cooling lines to IR luminosity).

Trends

- The [CII]/FIR ratio ≅ 0.004 for $L_{FIR} < 10^{11}$ and 60/100 < 0.6 but falls by an order of magnitude for $L_{FIR} > 10^{11}$ and 60/100 > 0.6.

- The [OI]/[CII] ratio rises with 60/100 (0.2 to ≥ 2) as [OI] begins to dominate the cooling at high temps. In some cases, XDRs contribute.

- The [CII]/PAH ratio is constant out to 60/100 > 1, confirming that PAHs are a prime contributor of photo-electrons.

*All estimates based on a 5σ, 1hr sensitivity of 5×10^{-21} W m^{-2} for BLISS + SPICA and 10^{-21} W m^{-2} for BLISS + CALISTO

Understanding Evolving, Dusty Galaxies at high-z

- The critical MIR diagnostics (including the PAHs) would be detected* in ULIRGs at z > 2 (5σ) in 15 mins with BLISS + SPICA. With CALISTO, we could measure ULIRGs out to z > 5, and LIRGs at z > 2. JWST + MIRI will measure the MIR diagnostics in faint IR galaxies out to z =1-1.5 (z=3.8 for 6.2 PAH alone).

- Both the [OI] and [CII] lines in LIRGs and ULIRGs at z > 2 (limited by λ_{max}) would be detectable (>10σ) in 5-10 mins with BLISS + SPICA. PACS will measure the most luminous galaxies at z=1-2, but only in long (1-few hr) exposures.

- With CALISTO, we could reach the same S/N in galaxies <u>below L*</u> at these epochs, and could detect [OI] from a galaxy with $L = 10^{10}\,L_{\odot}$ at z=5 in about 4-5 hrs. Combining [CII] 158, [OI] 63,145, [OIII] 52, 88, NII] 122, and [NIII] 57μm, with CALISTO & ALMA will constrain G_o, n_e, T_{eff} in LIRGs and ULIRGs over 2 < z < 7, <u>reaching the epoch of re-ionization</u>.

- Understanding (via statistically complete, large samples) the epochs where <u>rapid evolution</u> is taking place (z > 0.5 for LIRGs and z > 2 for ULIRGs), and studying <u>normal galaxies</u> at high-z requires platforms like SPICA & CALISTO with sensitive, moderate resolution (R≈1000), FIR spectrometers.

Armus et al. (2004, 2006, 2007); Brauher et al. (2008); Farrah et al. (2007); Helou et al. (2000, 2001); Luhman et al. (1998); Malhotra et al. (1997, 2001); Wolfire, Teilens & Hollenbach (1999);