Dense Molecular Gas in Atlas3D E and S0 Galaxies: ^{13}CO, HCN, HCO$^+$

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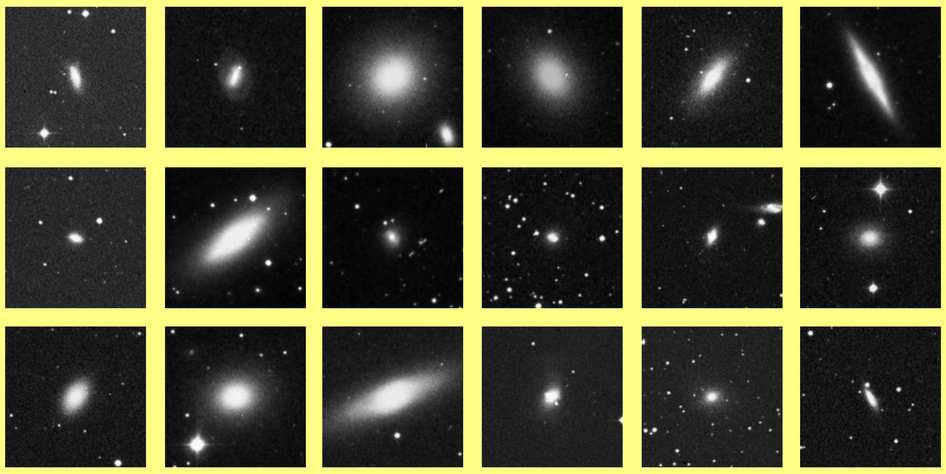
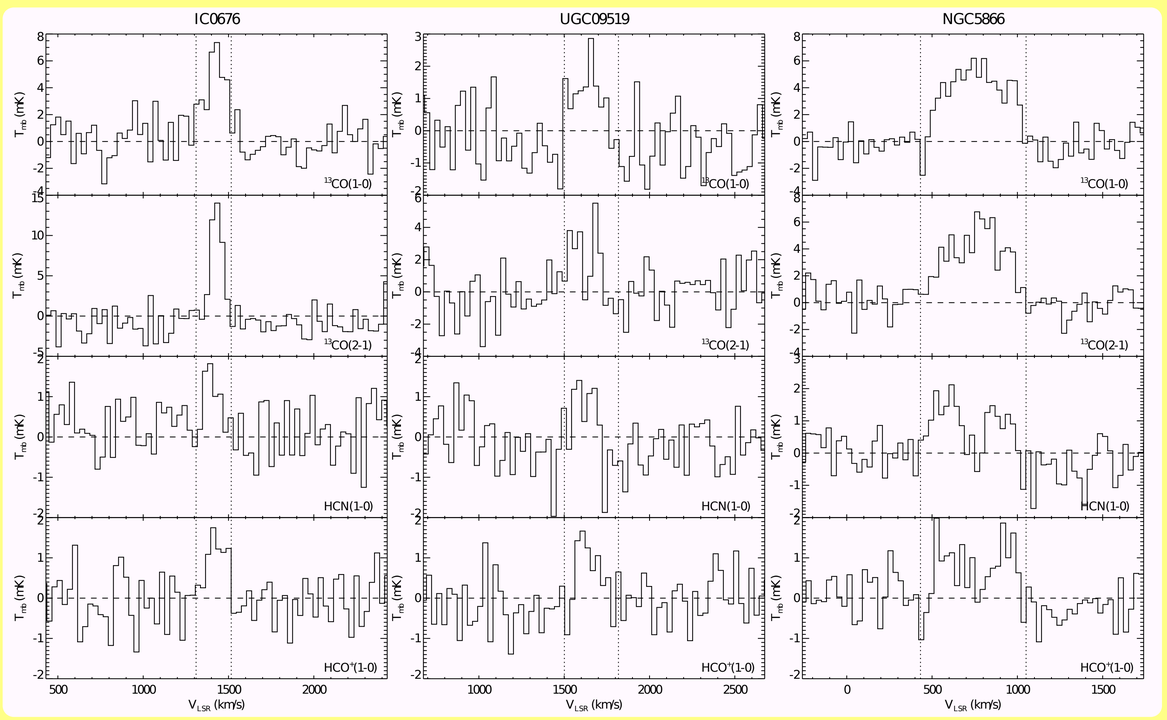
The Sample:

- 265 elliptical and S0 galaxies within 40 Mpc volume and observable from La Palma
- survey in ^{12}CO(1-0) at the IRAM 30m telescope $\approx$ 25% detected
- strongest 18 detections selected for this study (15 currently observed):



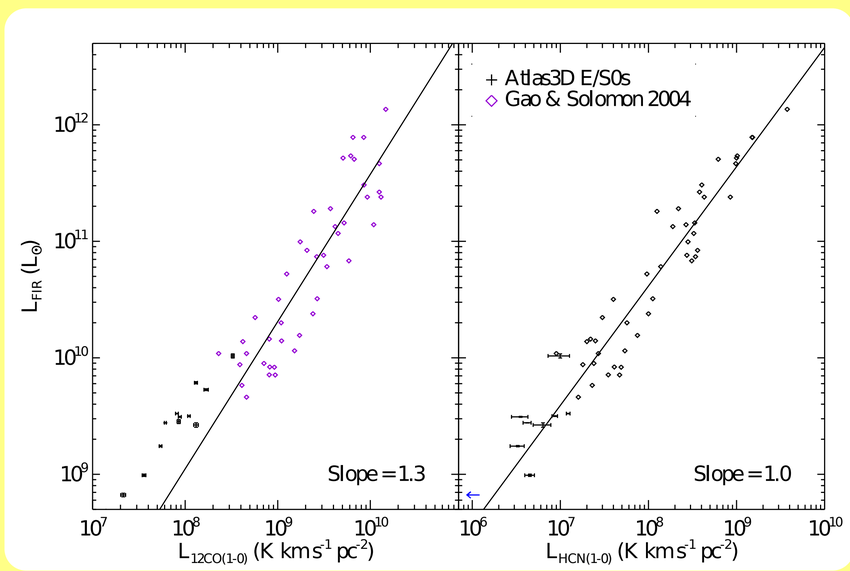
Observations and Data:

- observations to rms noise level of 1.1 and 0.6 mK for ^{13}CO(1-0) and HCN(1-0), respectively (30 km/s channels)
- 15/15 detected in ^{13}CO(1-0) and 14/15 in ^{13}CO(2-1)
- 9/11 detected in HCN(1-0) and 6/11 in HCO$^+$(1-0)
- Examples of lines in 3 galaxies:

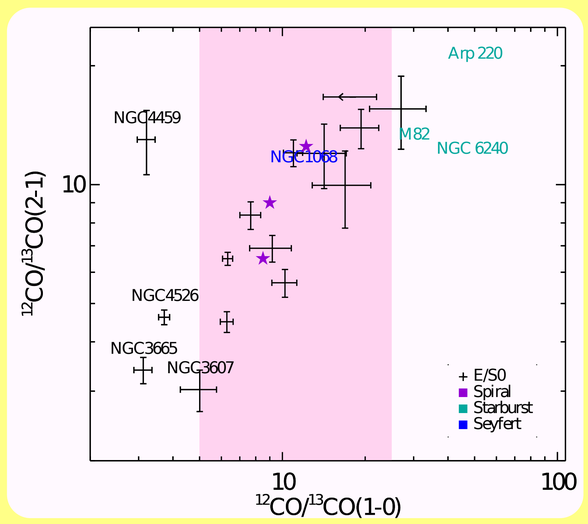


Spectra centered on the optical radial velocity. Vertical dotted lines indicate the region used to obtain integrated intensities (based on ^{12}CO(1-0) line width). All lines shown are over 3σ detections except for the HCN(1-0) line of UGC 09519.

Interestingly, the line profile of NGC 5866 shows a clear double peak structure in both HCN and HCO$^+$, while its CO lines show a single peak. This difference in shapes suggests a much lower dense gas ratio at low relative velocities, thus near the galaxy's center. This central drop in HCN is opposite to what is seen in XDR chemistry of some Seyferts where HCN is enhanced in the central regions.

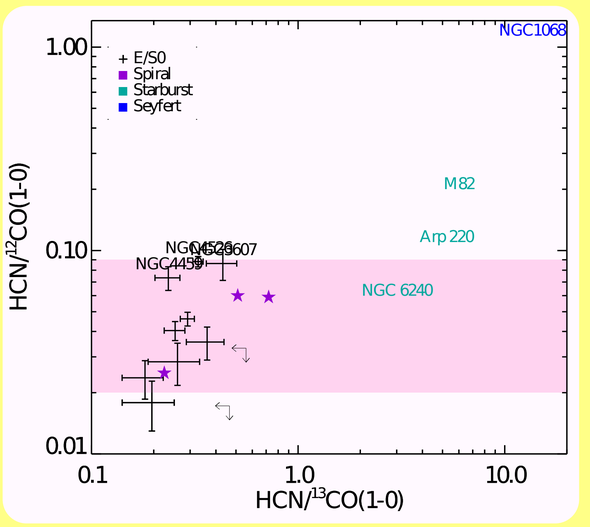


Line ratios:



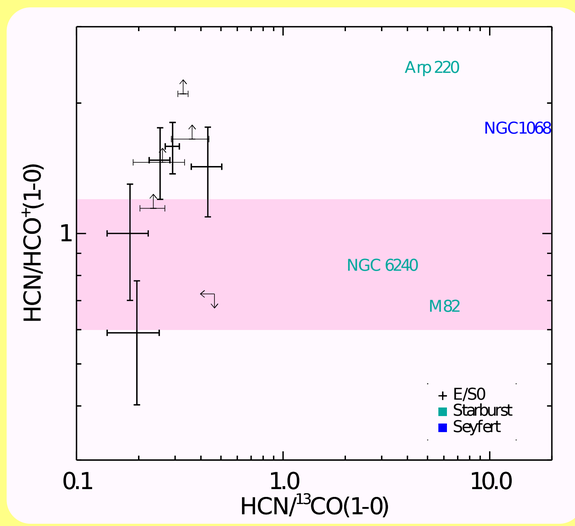
^{12}CO/^{13}CO

- measure of average optical depth
  - ^{12}CO/^{13}CO(1-0) ratio is between 5-25 for spiral galaxies (Paglione et al. 2000, pink region here)
  - higher ratios seen in starbursts with diffuse molecular gas (more ^{12}CO is optically thin)
  - lower ratios (<5) seen in Milky Way GMCs
- E/S0s span full range : various average optical depths
  - 3 galaxies with very low ^{12}CO/^{13}CO(1-0) ratios; possibly enhanced ^{13}CO abundance from old stars, possibly very optically thick
  - 1 galaxy with a high starburst-like ^{12}CO/^{13}CO(1-0) ratio: UGC09519
- ratios for the (1-0) and (2-1) transitions correlate
  - similar average gas properties within the smaller (2-1) radius beam
  - NGC 4459 sole outlier from the general trend



HCN/CO

- measure of dense molecular gas fraction
  - HCN/^{12}CO(1-0) ratio is between 0.2-0.9 for spiral galaxies (Gao & Solomon 2004, pink region here)
  - higher ratios seen in starbursts (more with ^{13}CO) and some Seyferts
  - even higher ratios seen in some Seyfert galaxies (see NGC 1068 in blue; hypothesis of XDR-influenced chemistry)
- E/S0s have similar dense gas fractions as spirals
  - nearly all E/S0s intersect with the spiral range of HCN/^{12}CO
  - the one upper limit clearly below is the same galaxy that approached the starbursts in ^{12}CO/^{13}CO ratio (UGC 09519); it thus has lots of optically thin molecular gas but is not similarly powered by a starburst (the low HCN/^{12}CO ratio reveals there is not enough dense gas)
  - the galaxies with very low ^{12}CO/^{13}CO(1-0) ratios have particularly high HCN/^{12}CO ratios; this fits with the hypothesis that they have a higher fraction of optically thick ^{12}CO



HCN/HCO$^+$

- measure of AGN/SN influenced chemistry
  - HCN/HCO$^+$ $\approx$ 1 in star-forming MW and M31 GMCs (pink region, Pirogov 1999, Brouillet et al. 2005)
  - HCO$^+$ enhanced by cosmic rays (ie. from SNe)
  - HCN can be enhanced by XDR chemistry surrounding powerful AGN (Lintott & Viti 2006)
  - AGN-dominated LIRGs have higher ratios, SB-dominated LIRGs have lower ratios (Krips et al. 2008, Imanishi et al. 2009)
- E/S0s vary significantly, most > 1
  - two below 1: UGC 09519 and NGC 2764; possibly SNe important for chemistry
  - several > 1.5: but not particularly powerful AGN... what causes such high ratios? denser than average GMC gas? metallicity effect?

SFR and molecular gas:

- SFR/CO or SFR/HCN trace how efficiently stars form from the molecular or dense molecular gas, respectively
- IR scales linearly with HCN, while the IR is overluminous with respect to CO in LIRGs and ULIRGs (linear fit has slope > 1, Gao & Solomon 2004)
- E/S0s lie above the relation found between IR and CO in the GS04 sample (have too much IR per CO, like LIRG/ULIRGs)
- much better agreement with the IR vs HCN relation; confirms idea that HCN is particularly good dense gas tracer and it is the dense gas that predicts SFR better than the total molecular gas