The Dense Molecular Gas in Galaxies

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Outline of this talk

• What are the star formation (SF) recipes? SF rate (SFR)--gas (HI, CO) scaling laws: Kennicutt-Schmidt law, other SF laws
• A linear FIR(SFR)--HCN (dense gas tracer) relation for all? star-forming systems (GMCs--->high-z?): SF law in dense gas
• Multiple lines, high-J CO/CS surveys
• Future @JCMT
Star formation (SF) laws

Schmidt (1959): \( SFR \sim \text{density}(\text{HI})^n \),
\( n = 1-3 \), mostly 2-3 in ISM of our Galaxy.

Kennicutt (1989): total gas

Disk-average \([SFR \sim \text{density}(\text{HI}+\text{H}_2)^n]\)
\( n \) is not well constrained. \( \sim 1-3 \), wide spread.

Kennicutt (1998): \( n = 1.4 \) ?

Total gas (\( \text{HI} + \text{H}_2 \)) vs. molecular gas

Gao & Solomon (2004): \( n = 1 \) in dense gas
(Hubble law and \( H_0 \) analogy)

(Schmidt 59, 63; Kennicutt 89, 98; Wong & Blitz 02; Heyer+04; Gao & Solomon 04;
Krumholz & McKee 05; Krumholz & Thompson 07; Bigiel+08; Robertson & Kravtsov
08; Gnedin+09; Krumholz+09; Daddi+10; Gnedin & Kravtsov 10; Ostriker+10;
Schruba+10; Genzel+10; Gnedin & Kravtsov 11; Narayan+11; Bigiel+11; Shi+11;
Liu+11; Rahman+11,12; Feldmann+11,12,13; Lada+12; Liu & Gao 12; Shetty+13).
Hubble law

FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.
Hubble law vs. SF law

• Hubble: 1 of 2 variables directly observed
• It’s a linear relationship!
• Yet >~70yrs $H_0$ measurements (wars)!!

?! SF: SFR a factor of 2-3 accuracy (much worse @hi-z)

?? Star-forming gas? HI, $H_2$ or dense $H_2$
  (~2-10 uncertainties, troubles?! ALMA!)

?! Might not be an exact linear relationship
  (even though FIR-HCN/CS linear!)

?? SF constant (SF law is still @infancy)
Disk-average $[\text{SFR} \sim \text{density}(\text{HI}+\text{H}_2)^{1.4}]$
Normal disk spirals
Ha->SFR & Size=D_{25}

IR circumnuclear starbursts
FIR->SFR & Size=CO/IR
SFR vs. M(H2): No Unique Slope: 1, 1.4, 1.7?

The fit lines: SFR = 1.4M(H₂)/10⁹ for SFR < 20M☉yr⁻¹ and SFR = 7.6(M(H₂)/10⁹)¹.⁷³ for all.

- Normal Spirals
- LIRGs/ULIRGs, L_IR > 10¹¹L☉
- Literature ULIRGs/LIRGs

HI ~ H₂

HI-dominated LSB galaxies

Extragalactic SF=CO until 90’s

SF thresholds may simply reflect the change of the dominant cold gas phase in galaxies from HI -> H2 & from H2-> dense H2 --> DCs/SSCs

Schruba+2011 ~ linear in H2!

Bigiel's talk @SFR50

Two major SF modes:
1. a long-lasting mode for disks (local spirals and BzKs)
2. a rapid starburst for LIRGs ULIRGs & SMGs/QSOs

CO->H$_2$ conversion factor
?? $\alpha_{\text{co}}$ (M$_{\odot}$ (K km/s pc$^2$)$^{-1}$:
  4.6 for local spirals
  3.6 ± 0.8 for BzKs
  0.8 for LIRGs/SMGs/QSOs

The fit line: \( \frac{L_{\text{IR}}}{L_{\text{HCN}}} = 863 \)
for \( L_{\text{IR}} < 10^{11} \, L_\odot \)

\[
\frac{L_{\text{IR}}}{L_{\odot}} = \text{SFR} \left( \frac{M_\odot}{\text{yr}^{-1}} / c_{\text{FR}} \right)
\]

\[
L_{\text{HCN}} \left( \text{K km s}^{-1} \text{ pc}^2 \right) = M(\text{denseH}_2) \left( M_\odot \right) / \alpha_{\text{HCN}}
\]

Dense Molecular Gas
Baan, Henkel, Loenen + 2008

HCN, CS, HNC etc. in SF gals.

- Bayet et al. (2009)
- Baan et al. (2008)
- Imanishi (2006)
- Solomon et al. 1992
- Nguyen et al. 1992
- Henkel et al. 1990
- Henkel, Baan, Mauersberger 1991

Best case studies:
Arp 220 & NGC 6240 (Greve + 2009)
Dense H$_2$ show the best correlation with SFR (linear Liu L & Gao 12).
Bi-modal SF laws in high-z (Daddi+2010; Genzel+2010) also exist in local galaxies

Liu L, Gao & Greve 14 in prep.
The fit line: $L_{\text{FIR}}/L_{\text{HCN}} = 700$
for $L_{\text{IR}} < 10^{11}L_\odot$
Wu, Evans, Gao et al. 2005 ApJL

Wu+2010

Fit to GMCs

Fit to Galaxies

Fit to both GMCs & Galaxies
Can DCs in nearby galaxies fill in the gap in FIR-HCN corr.?
- Total useful on-source integration time \( >\sim 110 \) hours.
- HCN spectra with \( S/N > 3 \) (a channel width \( dV \sim 7 \text{ km/s} \)).
- Typical rms \( \sim 1-2 \text{ mK} \) at \( dV \sim 20 \text{ km/s} \).
HCN contours are overlaid on the CO image.
Correlations between 8um-HCN & 24um-HCN. The solid lines: fixed slope of 1.
Multiple-J CS survey

Multiple transition from J=1-0 to 7-6 of CS lines towards ~50 nearby normal galaxies, starburst, and (U)LIRGs

CS J= 2-1/3-2/5-4 IRAM 30m
CS J= 5-4 (HH)SMT 10m
CS J= 7-6 APEX 12m

2009 ~ 2012

CS J= 1-0 GBT 100m
CS J= 1-0 EVLA

2010 ~ 2012

2009-2010

2011-2012
CS: better tracer of dense gas than HCN!

Wang, Zhang & Shi, 2011
Connecting with Galactic CS study \( \sim 10 \) orders of magnitude

CS J=2-1

\[ N = 1.07 \pm 0.03 \]

Galaxies

\[ N = 1.0 \]

Galactic cores

\[ N = 1.03 \pm 0.05 \]

Wu+2010

IRAM 30m
Connecting with Galactic CS study ~ 10 orders of magnitude

CS J=5-4

Galaxies

SMT 10m
IRAM 30m
Baan + 2008

Galactic cores

N=1.0
CS $J=7\rightarrow 6$, $N = 1.00 \pm 0.06$
Correlation Coefficient: 0.98

HCN $J=4\rightarrow 3$, $N = 1.06 \pm 0.06$
Correlation Coefficient: 0.98

HCOP $J=4\rightarrow 3$, $N = 1.34 \pm 0.10$
Correlation Coefficient: 0.95

Zhang, Gao, Henkel et al. 2014
• Dense gas over a range of $10^{4-8} \text{ cm}^{-3}$
Dust and Molecular Gas Heating

- While [CI] 370 μm [or low-J CO lines such as CO(4-3)] correlate apparently with $L_{IR}$, CO(6-5) is more tightly correlated with $L_{IR}$, even at the “low luminosity” end.
  - There is a relative cold gas component that is not or less directly associated with SFR.

- Combining a few mid-J CO lines improves the scatter, at both low and high luminosity ends, leading to a better one-to-one correlation with $L_{IR}$.
  - This well-defined one-to-one correlation traces mainly the PDR gas/dust heating.
Future JCMT Dense Gas Obs.

- HCN/HCO+/HNC J=3-2, 4-3 etc. (Fuller)
- CO J>=3 (Wilson & Herschel/FTS), CS5-4
- Both single-pointing and mapping obs.
- SCUBA2: S(L)EDs, Dust-gas ratio

\[ \text{HI} \rightarrow \text{H}_2 \rightarrow \text{DENSE H}_2 \rightarrow \text{Stars} \]

Schmidt law: HI(gas reservoir) \(\rightarrow\) Stars
Kennicutt: HI(gas reservoir) + H\(_2\)(fuel?) \(\rightarrow\) Stars
Gao & Solomon: Dense H\(_2\) (fuel !!) \(\rightarrow\) Stars

**From Cores to High-z: Dense Gas \(\rightarrow\) Massive SF**

HI=gas reservoir HI (FAST) is an excellent tracer of galaxy interactions: kinematics/morphology; evolution & environments (not for SF). H\(_2\) OK for SF, yet dense H\(_2\) is best (Antarctic Dome-A)!