The Kennicutt-Schmidt Star Formation Relation at z~2

Desika Narayanan
Harvard-Smithsonian CfA

Chris Hayward
Harvard

T.J. Cox
Carnegie

Lars Hernquist
Harvard
Kennicutt-Schmidt SFR Laws

Molecular Kennicutt-Schmidt SFR Laws

Local: CO J=1-0
n=1.5

\[ \text{Total H}_2 \text{ Gas Mass} \]

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

\[ L_{IR} = 33 L_{C0} \]
for \( L_{IR} < 10^{11} L_\odot \)

Gao & Solomon 2004

z~2: CO (J=3-2)

z~2 Bouché et al. 2007
Theoretical Approach: SPH simulations of galaxies

Prescriptions for multi-phase ISM (McKee-Ostriker)

SF (volumetric Schmidt law)

BH growth and associated Feedback

Halos scaled to z~2 concentration

For z~2 study, isolated galaxies $M_{\text{bar}} \sim 10^{11} M_\odot$, MMW disks

SF follows SFR $\propto \alpha^{1, 1.5, 2}$

Springel et al. (2003-2005), Hopkins et al. 2006
Non-LTE Radiative Transfer (Synthetic Molecular Line Emission)

- 3D Monte Carlo code developed based on improved Bernes (1979) algorithm
- Considers full statistical equilibrium with collisional and radiative processes
- Sub-grid algorithm considering mass spectrum GMCs as SIS; $M_{\text{cloud}}=10^4-10^6 M_\odot$ (Blitz et al. 2006, Rosolowsky 2007)
- Uniform Galactic CO Abundance, no H$_2$ at $N_H < 10^{21}$ cm$^{-2}$

CO $J=1-0$, CO $J=2-1$, CO $J=3-2$, CO $J=4-3$, CO $J=5-4$, CO $J=6-5$, CO $J=7-6$, CO $J=8-7$, CO $J=9-8$

1.2 kpc

DN+ 2006, 2008
SUNRISE (dust RT) to ‘Select’ Galaxies

Physics Included in Monte Carlo IR RT:
- IR transfer of stellar and AGN spectrum (starburst 99 for stars and Hopkins+ 07 for AGN)
- dust radiative equilibrium
- Kroupa IMF, MW DTM, Draine & Li Dust
- Stellar Clusters surrounded by HII regions and PDRs (MAPPINGS; Groves et al. 2008)

Jonsson, Groves & Cox (2009)
Does Differential Excitation Matter?:
Local Universe Example

**CO (J=1-0)**
\[ n_{\text{crit}} \sim 10^2 \text{ cm}^{-3} \]

Gao & Solomon 2004

**CO (J=3-2)**
\[ n_{\text{crit}} \sim 10^4 \text{ cm}^{-3} \]

Iono et al. 2008

**SFR ~ CO (1-0)**
\[ 1.5 \]

**SFR ~ CO (3-2)**
\[ 0.9 \]

Narayanan et al. 2005
Molecular Kennicutt-Schmidt SFR Laws

**CO J=1-0**

\[ n_{\text{crit}} \sim 10^2 \text{ cm}^{-3} \]

**HCN J=1-0**

\[ n_{\text{crit}} \sim 10^5 \text{ cm}^{-3} \]


Index = 1.5

Index = 1.0

SF follows SFR \[ 1.5 \]
Molecular Kennicutt-Schmidt SFR Laws

**CO (J=1-0)**

\[ n_{\text{crit}} \sim 10^2 \text{ cm}^{-3} \]

\[ \text{SFR} \sim \text{CO (1-0)}^{1.5} \]

Gao & Solomon 2004

**CO (J=3-2)**

\[ n_{\text{crit}} \sim 10^4 \text{ cm}^{-3} \]

\[ \text{SFR} \sim \text{CO (3-2)}^{0.9} \]

Narayanan et al. 2005

Iono et al. 2008
Differential Excitation; Underlying $n=1.5$ KS Index

SF follows SFR $^{1.5}$

Krumholz & Thompson 2007
Narayanan et al. 2008a,b
HCN (J=3-2) Observational Survey

Bussmann, DN, Shirley, Wu, Juneau et al. (2008)
Juneau, DN, Moustakas, Shirley et al. (2009)
HCN (J=3-2) Observational Survey

Bussmann, DN, Shirley, Juneau et al. (2008)
Juneau, DN, Moustakas, Shirley et al. (2009)
Getting to the KS Relation at $z \sim 2$: Models of High-z Galaxies (SMGs, BzKs)

(Narayanan, Hayward et al. 2009, 2010)

Hayward, Narayanan et al. in prep.
Getting to the KS Relation at $z \sim 2$

Narayanan, Cox, Hayward, Hernquist in prep.

SF follows SFR $1, 1.5, 2$
Getting to the KS Relation at $z \sim 2$

Narayanan, Cox, Hayward, Hernquist in prep.

SF follows SFR for $K_S = 2$ galaxies

$SFR - L_{CO}$ index versus Transition for $K_S = 2$ galaxies
Getting to the KS Relation at $z \sim 2$
Narayanan, Cox, Hayward, Hernquist in prep.

**SFR-L$_{\text{CO}}$ index versus Transition for KS = 2 galaxies**

SF follows SFR $\propto 1, 1.5, 2$
Mapping the CO 3-2 KS relation at z~2 to the underlying volumetric Schmidt Relation

Narayanan, Cox, Hayward, Hernquist in prep.

Data from Tacconi et al. 2010:

\[ \text{SFR} \sim L_{(\text{CO3-2})}^{0.97} \]

Physical KS index vs. SFR-CO (J=3-2) index
Conclusions

1. Excitation Matters

CO (J=1-0)
\[ n_{\text{crit}} \sim 10^2 \text{ cm}^{-3} \]

CO (J=3-2)
\[ n_{\text{crit}} \sim 10^4 \text{ cm}^{-3} \]

SFR \sim CO (1-0)^{1.5}

Index = 1.0

SFR \sim CO (3-2)^{0.9}
Conclusions

2. At High-z KS Relation may be consistent with 1.5