Studying galaxy evolution with SMA CO(2-1) 
B0DEGA (Below 0 DEgree GAlices)

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Outline

• Globally: How environment affects the molecular gas content and star formation?

• Locally: How interactions affect the distribution and kinematics of molecular gas? Is molecular gas content enhanced by interactions?

• The missing reference sample:
  • high resolution molecular gas observations of a well-defined sample of isolated galaxies
ISM, Star Formation and Environment

M31

- Interplay ISM and SF.
- Nurture vs Nature on galaxy evolution
- Interaction = ↑ Complexity
ISM, Star Formation and Environment

- **Kennicutt-Schmidt law**: $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.4}$.

- $L_{\text{FIR}}/M_{\text{H}_2}$ is a good estimate of star formation efficiency (SFE).

- In normal spiral galaxies SFE = 1 - 3, in starburst $\sim 20$ and ULIRGs is $>100$ Lo/Mo.

- Directly linked to the environment: SFE seems to be higher in perturbed galaxies.

**Figure**: Sanders & Mirabel 1985
Star formation laws

- $L_{\text{FIR}} - L_{\text{HCN}}$ correlation index $N = 1$ holds well from dense cores with $L_{\text{FIR}} > 10^5 L_{\odot}$ to LIRGs/ULIRGs.

Which molecular gas tracer is more adequate? CO, HCN, HCO+,..? Are some molecules more fundamental than others in relation with SF?


Wu et al. (2005)
Star formation laws

- SFR-CO and HCN indexes.
- SPH, non-LTE radiative transfer.
- Just assuming constant Schmidt law index: SFR $\propto n^{1.5}$.
- Index depends on how $n_{\text{crit}}$ relates to $<n>$ for a given line.

(Narayanan et al., 2007; see also Krumholz & Thompson 2007)
From global to local SF laws

- 18 nearby galaxies, non starbursts galaxies.
- CO(2-1) IRAM 30m, 750 pc resolution.
- KS law $\Sigma_{SFR}$ and $\Sigma_{H2}$ index point to point: $N = 1.0 \pm 0.2$.
- In spirals the SFE function of radius.

THINGS: Bigiel et al. (2008)
High-resolution molecular gas surveys

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- High complexity (morphology, kinematics, activity). No statistics possible...
- Transitions > 1-0 needed to trace warmer and denser gas.
- CO(2-1): similar $T_B$, $n_{crit} = 10^{3-4} cm^{-3}$, $T = 15$ K. Higher resolution.
## High-resolution molecular gas surveys

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### Diagram

- **BIMA-SONG**
- **OVRO-NRT**
- **SCONES**
- **NUGA**
- **SMA BODEGA**
- **LIRGs/ULIRGs**

**Axes:**
- Log(FIR)
- Number of objects

**Projects:**
- BIMA-SONG
- OVRO-NRT
- SCONES
- NUGA
- SMA BODEGA
- LIRGs/ULIRGs
**SMA CO(2-1) BODEGA (Below 0 DEgree GAaxies)**

- Characterize molecular gas properties: **morphology**, concentration, asymmetries, **kinematics**, physical conditions.

- How molecular gas relates to **SF**, globally, radially, and point to point.

- How molecular gas respond to extreme environments such as **starbursts and AGNs**.

- How molecular gas respond to **interactions**. What is its relation with atomic gas.
- CO(2-1) for unexplored southern hemisphere galaxies.
- N~21 already observed IR-bright galaxies (up to ~100). Spirals with bar. Signs of perturbation, but not mergers.
- Other observations and archival data: HI (VLA, ATCA), mid-IR (Spitzer), Ha (1m-2m telescopes), UV (GALEX).
- Technical: Pipeline (imaging and analysis), Database, Web to put data publicly available.
SMA CO(2-1) BODEGA (Below 0 DEgree GAaxies)

I. CO(2-1) atlas of southern sources

II. Global properties:  $L_{\text{FIR}} - \text{CO}(2-1)$

III. CO(2-1) concentration and environment

IV. $^{12}\text{CO}/^{13}\text{CO}$ radial distribution
I. CO(2-1) Atlas of southern sources

- N = 21 galaxies observed. FOV = 1’, resolution = 3’’. 
- CO(2-1), $^{13}$CO(2-1) detected and sometimes even C$^{18}$O(2-1). 
- Different morphologies: circumnuclear disks, spiral arms, rings.
I. CO(2-1) Atlas of southern sources
II. Global properties: $L_{\text{FIR}} - ^{12}\text{CO}(2-1)$

![Graphs and histograms showing the relationship between various astronomical parameters.](Image)

- $\text{slope} = 1.15$, $p = 0.91$
II. Global properties: \( L_{\text{FIR}} - ^{12}\text{CO}(2-1) \)

- SPH, non-LTE radiative transfer.

- Schmidt law index, \( \text{SFR} \propto \rho^{1.5} \)

- Index depends on how \( n_{\text{crit}} \) relates to \( \langle n \rangle \) for a given line.

\[-\text{SFR} - \text{CO}(2-1) \text{ slope agrees with predicted SFR-CO index.}\]

(Narayanan et al., 2007; see also Krumholz & Thompson 2007)
III. CO(2-1) distribution

- 90% of the galaxies peak in the center (unlike CO(1-0)!) Different sample characteristics, or excitation conditions?
- Size is ~ 500 pc, circumnuclear disks.
- Extended features such as arms and rings.
III. CO(2-1) distribution and SFE

- In normal spiral galaxies SFE = 1 - 3, in starburst ~ 20 and ULIRGs is >100 Lo/Mo.

- Most of B0DEGA galaxies are starburst in terms of SFE: 8 - 43 Lo/Mo.

-Highest SFE in galaxies with small CO(2-1) size, but not barred galaxies nor interacting.

-Lowest SFE is not correlated to less concentrated CO(2-1): Extended features, rings and arm shape have normal SFE ~10-20 Lsun/Msun.
III. CO(2-1) distribution and environment

- Largest amount of molecular gas: interacting systems (~ $10^{10} M\odot$, NGC3110, NGC232), rather than barred galaxies.
- Fly-by interactions is a very efficient mechanism to fuel gas to the central regions!
- Are we seeing two evolutionary stages of same mechanism?

NGC3110
Mgas=9.2 $10^9$ Msun
SFE=10

NGC232
Mgas=8.0 $10^9$ Msun
SFE=17
IV. $^{12}\text{CO}(2-1)/^{13}\text{CO}(2-1)$ radial distribution

$R_{12/13} \sim 10$ in active disk galaxies (Sakamoto et al. 2005)

$R_{12/13} > 20$ (Casoli et al. 1992)

... or external gas, less processed gas (Henkel et al. 1991)
Perspectives for B0DEGA

• CO(2-1) Atlas of IR-bright galaxies in the southern hemisphere.
• Legacy Program at SMA? N ~ 100 southern galaxies.
• Radial, point to point properties: SF laws SFR-CO, $^{12}$CO/$^{13}$CO.
• Comparison other samples, non-starburst, ULIRGs, etc.
• Comparison with atomic gas properties.
• SMA is unique for this project:
  - Large field of view: inner 3 kpc of galaxies.
  - Large bandwidth: ~ 3 galaxies (with similar vel.) in 1 track.
  - Good site: usually bad weather means good for CO(2-1),
even day-time observations.
3.12CO(2-1)/13CO(2-1) Radial Distribution

\[ R_{12/13} = \frac{(1 - e^{-\tau_{12}}) [J(T_{ex,12}) - J(T_{CMB})] f_{b,12}}{(1 - e^{-\tau_{13}}) [J(T_{ex,13}) - J(T_{CMB})] f_{b,13}} \]