The molecular connection to the FIR-RC correlation in Nearby Galaxies

Rosita Paladino

Università di Bologna - INAF IRA
Magnetic field

Part. Accl.

SN

ISM Shocks

SNR

Hot stars

Heating

Warm Dust

FIR

Radio continuum

Synchrotron

Transport

CR

Part. Accl.

CR

CR

Magnetic field

Ron Ekers sketch 1991

FIR-RC Correlation!

Stars form

Heating

UV

UV

Heating

FIR

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CO et al

Molecular clouds

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UV

UV

Magnetic field
Link between molecular and FIR

- e.g. Young & Scoville 1991

“Direct” connection between dust and molecular emission.

The ratio between IR luminosity and H2 mass is closely correlated with dust temperature.
CO(3-2) observations obtained with JCMT of a sample of SINGS galaxies (filled symbols) and luminous and ultraluminous infrared galaxies, at low and high redshift (open symbols)

Depletion time obtained from the ratio $\sim 3$ Gyrs for normal disk galaxies

50 times shorter in local and high-z ULIRGs

Wilson et al., 2012
Link between molecular and FIR

Recent APEX observations of CS, HCO+ and HCN

Linear correlations:

\[
\begin{align*}
L_{\text{CS}} & \propto L_{\text{FIR}} \\
L_{\text{HCN}} & \propto L_{\text{FIR}} \\
L_{\text{HCO+}} & \propto L_{\text{FIR}}
\end{align*}
\]

Zhang et al., 2014
RC – molecular correlation on global scales

- First CO detection in external galaxies: **Rickard et al. 1975**
  Many single dish studies

- Correlation between molecular and synchrotron emission
  (e.g. **Rownd & Young, 1999; Adler et al, 1991**)

- **Murgia et al. 2002**
  Comparison of NVSS and **FCRAO CO**
  180 objects at 45 arcsec resolution.

  Spatially resolved correlation including all morphological types and starbursts.

  Star formation efficiency deduced from the radio continuum, corresponds to convert 3.5% of the available molecular gas into stars on a time scale of $10^8$ yrs.

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**Murgia et al., 2002**

![Graph showing correlation between radio continuum and CO emission](image-url)
An analogous correlation at kpc spatial scales has been found in a sample of 28 dwarf galaxies.
A tight global correlation has been observed between HCN (dense gas tracer) and RC (e.g. Gao & Solomon, 2004; Liu et al., 2010).

A study of the global star formation law in a sample of 181 galaxies (normal spirals, and ULIRGs) IR luminosity spanning five orders of magnitude.

No correlation between HI and SFR.

The tightest relation in the sample is the linear relation between SFR (traced both by IR and RC) and dense gas traced by HCN emission.

Liu et al., 2015
Spatially resolved observations of nearby galaxies

- High resolution observations:
  - Nobeyama and Owens Valley Millimeter Array
  - CO(1-0) observations of the central arcmin of 20 galaxies @ 4” resolution

[Images of galaxy maps labeled NGC 4321, NGC 5248, NGC 6946, NGC 5194, NGC 2903]
High resolution observations:
BIMA Survey Of Nearby Galaxies (SONG; PI: M.W.Regan and T. Helfer)
BIMA and 12 m single dish CO(1-0) observations of 44 galaxies 6” resolution

Regan et al., 2003; Helfer et al., 2003
Spatially resolved observations of nearby galaxies

- High resolution observations:
  NUclei of GAaxies (NUGA, PI: S. Garcia-Burillo and F. Combes)
  Plateau de Bure CO(1-0) and CO(2-1) observations of the central 1 kpc regions of 30 galaxies @ < 1” resolution
Spatially resolved observations of nearby galaxies

- High resolution observations:
  CARMA Survey Towards Infrared-bright Nearby Galaxies (STING; PI: A. Bolatto and T. Wong)
  CARMA CO observations of 23 galaxy disks @ 3” resolution

Nurur et al., 2011
High resolution observations:

- PdBI Arcsec Whirlpool Survey (PAWS; PI: E. Schinnerer)
- PdBI and 30 m CO(1-0) observations of the central ~9 kpc of M51 @ 1”, 3”, 6” resolution

Schinnerer et al., 2013
RC-CO local correlations

In a sample of 22 CO luminous galaxies from the BIMA SONG
Spatially resolved correlation between 1.4 GHz emission and CO(1-0)
holds down to spatial scales of hundreds of pc

Paladino et al., 2006
It is actually a 3D correlation between RC-FIR-CO

Example obtained for 6 galaxies @ 6” resolution

Paladino et al., 2008
Good spatial correlation of low-frequency RC and CO line emission.

Pixel by pixel comparison @ 3” resolution
Steeper and stronger in the central disk. The RC emission in the central region is brighter for a given CO flux independently on the AGN

Schinnerer et al., 2013
Theoretical models

Stars form

SN

SNR

ISM Shocks

Molecular clouds

Intriguing correlation since RC emission is only indirectly linked to star formation

CO/HCN-RC Correlation!

Radio continuum

Synchrotron

CR

CR

Transport

Part. Accl.

CR

Magnetic field

Radio continuum
Cosmic Ray heating
(Adler et al., 1991; Suchkov et al., 1993)

- “Attractive” direct links between CR and molecular clouds
- Does NOT justify the observed correlation spanning 3 orders of magnitude in both RC and CO emission
- M51 PAWS results argue against it
Secondary electrons hypothesis
(Marsher and Brown, 1978; Murgia et al., 2005; Thompson et al., 2007)

- Non-thermal spectral index analysis...
- Too many parameters involved
- No successful detection of non-thermal emission from secondary electrons in Galactic Clouds (e.g. Protheroe et al. 2008)
Theoretical models

Coupling between gas density and magnetic field
(e.g. Niklas & Beck, 1997; Murgia et al., 2005; Schinnerer et al., 2013)

CR electrons with energy spectrum

\[ N(\epsilon) = N_0 \epsilon^{-\delta} \]

produce a non-thermal radio emission with spectral index

\[ \alpha = (\delta - 1)/2 \]

\[ I_{RC} \propto N_{CR} B^{\alpha + 1} \nu^{-\alpha} \]

Assuming coupling between gas density \( \rho \) and magnetic field strength \( B \)

\[ B \propto \rho^\beta \]

What mechanism/parameter produces the coupling? Murgia et al. (2005) proposed the hydrostatic pressure

The gas surface density is the projection of the volume density through the disk

\[ \Sigma_{gas} \sim \rho \]

\[ I_{RC} \propto N_{CR} \Sigma_{gas}^{\beta(1+\alpha)} \]
The state of the art

the highest spatial resolution correlation obtained with PAWS M51 data

What would be needed to go forward:

A statistical sample of galaxies observed at high spatial resolution

Sensitive RC observations to further test the role of magnetic field

Spatially resolved non-thermal spectral index maps

Study the magnetic field at giant molecular cloud scale and its connection with the galactic magnetic field (e.g. M33 observations; Li et al. 2011)
The state of the art M51 PAWS map has been obtained in ~200 hrs of PdBI observing time

mapped area 11x7 kpc
resolution ~1"
rms 0.4 K in 5 km/s

ALMA cycle 3 (36 antennas) would have obtained the same sensitivity covering the same area in a M51-like galaxy (@ LMC position) in ~18 hrs
Future perspectives with ALMA

- ALMA will allow a step forward in spatial resolution
  - kpc scale
  - ~100pc spiral arm
  - 10pc GMC scale
- and a step forward in sensitivity
  - Spatially resolved correlation between dense gas tracers and RC are still missing
  - Global scale
Link between molecular and FIR

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Further steps

Future perspectives with ALMA

Grazie