Linking Galactic and Extragalactic Gas and Dust Surveys

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Outline

• Atomic/molecular phase evolution in spiral galaxies (atom-dominant vs molecule-dominant)

• Development of small dense clumps in the ISM (w.r.t. spiral arms)
Gas Phase
Atom Dominant Case
Classic Picture of ISM Evolution

Diffuse (Atomic) Gas

Bound (Molecular) Gas

Dense Gas

Young Stars

Provided by Adam Leroy
M33 - GMCs on HI Spiral Arms

GMC lifetime
~ Arm crossing timescale
~20-30Myr?

Engargiola et al. 2003
GMC Evolutionary Sequence in LMC

Kawamura et al. 2009

24%  ~6Myr

50%  ~13Myr

26%  ~7Myr

GMC lifetime ~ 20-30Myr

~66% of young clusters (<10Myr) are associated with GMCs.

Complete >5x10^4Msun

~20-40Myr in M33 (Miura et al. 2012)
Angular Size

Standard picture: based on MW outskirts (around Sun) & dwarf galaxies
 Atom-rich
LMC, M33,
(Outskirts of MW, etc)

Molecule-rich
Disks (major parts) of
M51, MW, etc.

What about the main parts of major disk galaxies?
Gas Phase:
Molecule Dominant Case
Coagulation and fragmentation of GMCs

Classic picture: rapid phase transition

atomic H

molecular H₂

Velocity gradients
Molecular Fraction

\[ f_{\text{mol}} = \frac{\sum H_2}{\sum H_2 + \sum H_1} > 70\%-80\% \]

Little Azimuthal Change

Not much atomic H in interarm regions
GMC Distribution

GMC evolution
Large (arm) → Small (interarm)

CARMA+Nobeyama- Koda et al. 2009

Koda et al. 2009
The Astropysical Journal at high cloud masses (e.g., Fukui et al.)

structures, while for values

values

in different M51 environments. The equivalent values of CO

number density of GMCs) and a horizontal offset (i.e., a different maximum cloud mass), as well as the different distribution shapes. The equivalent C

for exact area) and to the total number of clouds for each environment (right). The distributions clearly exhibit both a vertical offset in the left pan

is higher in the center than the spiral arms, and higher in the spiral

in the top right corner of the panels in Figure

M

γ

0

is the maximum mass in the distribution and

N

γ

5.0

<

Rin

M

g

0

([L

γ

+1

]"

kpc

×

5

10

⊙)

This is also evident for the GMC mass distribu-

inter-arm, while the mass distribution in the material arms has

very few clouds with masses greater than 10

7.0

than a reference mass

mass spectra using a truncated power law (Williams & McKee

2001

where the mass distributions show more re-

mass distribution of downstream GMCs reaches slightly higher

Colombo et al. 2014

GMC	

distribu;on

GMC	

mass	
unc;on

Cumulative/Normalized
GMC mass function

Nuclear Bar
Molecular Ring
Dens-Wave Arms In
Dens-Wave Arms Out
Material Arms
Downstream
Upstream

GMC evolution
Large (arm) ➔ Small (interarm)
Gas Phase in the MW
Milky Way

Molecular Fraction ($f_{\text{mol}}$) in $l$-$v$ diagram

\[ f_{\text{mol}} = \frac{\Sigma H_2}{\Sigma HI + \Sigma H_2} \]

$f_{\text{mol}}$ - independent of heliocentric distance

Koda in prep.
**l-v diagram**

### Flat circular rotation

\( V_0 = 220 \text{km/s}, R_0 = 8.5 \text{kpc} \)

### Spiral arms in l-v

*Logarithmic spiral from GLIMPSE (Churchwell et al. 2009)*

- Non-circular motion
- + velocity dispersion

**Trace both arm and interarm in l-v**

\((l, v) \) to \( R_{\text{GAL}} \)
Koda in prep.
Primarily radial gradient

$f_{\text{mol}} > 50\%$ at $R < 6 \text{kpc}$
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Azimuthal variations

Only 20-30\%
Primarily radial gradient

$f_{\text{mol}} > 50\%$ at $R < 6 \text{kpc}$

Azimuthal variations

Only 20-30\%
Dust -- Dark Gas
Dark gas

mostly HI (HI 21cm)  mostly H$_2$ (CO 1-0)

Excess due to dark gas

$|b| > 10\,\text{deg}$

Proportional to total gas

| $|b| > 10\,\text{deg}$ | Fraction |
|----------------------|----------|
|                      | $\sim 22\%$ |

Planck Collaboration 2011a,b
CO-dark H$_2$?: Photo-dissociation of H$_2$ and CO

**Line absorption**

(photoelectronic effect --> exceed $E_{\text{bind}}$)

- Self-shielding (by H$_2$ or CO)
- Mutual-shielding (by H&H$_2$ lines, by CO isotopes)

**Dust attenuation**

- High-metallicity
  - Less dust attenuation

- Low-metallicity
  - Low CO abundance
  - High dust attenuation

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Wolfire, Hollenbach & McKee 2010
Conceptually, CO-dark H₂ can be calculated as follows:

\[ \text{CO-dark H}_2 = N_{H+H_2}\text{ from [CII]} - N_H\text{ from HI 21cm} - N_{H_2}\text{ from CO(J=1-0)} \]
Optically-Thick HI?

One can find a solution of cold, optically-thick HI gas to explain all dark gas.

HI optically-thin regions for calibration:

\[ \tau_{dust} \rightarrow N_{HI} \]

HI optically-thicker regions:

Two equations for \( T_{spin} \) and \( \tau_{HI} \)

1. Spontaneous emission

\[ \tau_{HI} \approx \frac{3c^2}{32\pi} \frac{A_{HI} N_{HI}}{\nu_{HI}} \frac{h}{kT_{spin}} \frac{1}{\Delta V_{HI}} \]

2. Radiative transfer

\[ W_{HI} = (T_{spin} - T_{bg}) \left[ 1 - e^{-\tau_{HI}} \right] \Delta V_{HI} \]

85% of the total HI gas

\[ \tau_{HI} \sim 0.5 - 3 \]

\[ T_{spin} \sim 10 - 60K \]

A question from HI absorption studies (Stanimirovic et al. 2014)
Structures w/i Clouds
Nearby Clouds observed with Herschel
filaments and clumps

Probability distribution function

Avles de Oliveira et al. 2014
Quiescent vs Star-forming Local Clouds

Extinction mapping $\rightarrow$ Probability Distribution Function

23 molecular clouds within 500pc distance from the Sun

Kainulainen et al. 2009
Growth of Dense Clumps

$^{12}$CO Obs. of $\sim 38^\circ$ region with Nobeyama 45m telescope
Channel maps: 50 arcmin x 50 arcmin, 15" resolution (<0.7pc)

Sawada et al. 2012
Brightness Distribution Function (BDF)

$T_{\text{MB}} \text{[K]}$ in CO(1-0) $\sim$ column density

High column density gas in spiral arms

Sawada et al. 2012
Brightness Distribution Function (BDF)

Probability Distribution Function (Kainulainen et al. 2009)

Spiral arm

Interarm

Fraction of pixels

35–40 km s$^{-1}$

HPBW = 17$''$

HPBW = 51$''$

BDI = −0.74

50–55 km s$^{-1}$

BDI = −1.17

65–70 km s$^{-1}$

BDI = −2.78

80–85 km s$^{-1}$

BDI = −2.69

Log (N/N$_{peak}$)

$A_v$ [mag]

star—forming clouds

quiescent clouds

2x10$^{22}$ 4x10$^{22}$ cm$^{-2}$

2x10$^{22}$

4x10$^{22}$ cm$^{-2}$
Brightness Distribution Index (BDI)

Characterize distribution with one parameter

\[ BDI = \log_{10} \left( \frac{\int_{T_0}^{T_3} T \cdot B(T) dT}{\int_{T_0}^{T_1} T \cdot B(T) dT} \right) \]

\((T_0, T_1, T_2, T_3) = (3, 5, 10, \infty)\)
Growth of Dense Clumps in Spiral Arms

BDI in each 2degx1degx5km/s grid

Sawada, Hasegawa & Koda 2012
Summary

- Gas phase evolution with galactic revolution
  - Globally atom-dominant region
    - Atom/mol/atom transition across spiral arms
  - Globally molecule-dominant region
    - Very small variation. gas stays molecular
  - Dark gas
    - ~30% of total gas with uncertainties

- Dense structures within clouds
  - Develop in spiral arms
  - PDF: similar to log-normal (interarms) and power-law (arms)