Galaxies  Astro 530
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Molecular Gas in Galaxies &
Measuring Star Formation Rates in Galaxies
Importance of Molecular gas

1.) it’s the medium in which stars form

2.) $\text{H}_2$ dominates the ISM mass in centers of gas-rich galaxies; may be dominant form of mass in centers of some galaxies (exceeding mass in stars and dark matter)
relations between CO emission and H$_2$ mass

\[ N(H_2) = X \text{ I}_{CO} = \left( \frac{X}{\Omega_b} \right) \int \int T_b(v, \Omega) \, d\Omega \, dv \quad (\text{K km/s}) \]

doesn’t work for indiv lines-of-sight, only works if averaged over a whole cloud or many clouds

\[ X \sim 2 \times 10^{20} \frac{\langle n/200 \text{ cm}^{-3} \rangle^{1/2}}{\langle T/6 \text{K} \rangle} \quad \text{H}_2 \text{ cm}^{-2} (\text{K km/s})^{-1} \]

\[ M(H_2) = 8.0 \times 10^3 \frac{X}{2.0 \times 10^{20}} D^2 \int S_{CO}(v) \, dv \]

these equations valid if:

a. clouds close to Virial Equilibrium
b. cloud properties similar to local Milky Way clouds
c. $Z > 0.5 \, Z_{\odot}$ [ if $Z < 0.5 \, Z_{\odot}$ then $d_{CO} < d_{H_2}$ ]
“classical” size-linewidth relation for molecular clouds

- Size-linewidth relation for molecular clouds in nearby Milky Way $\sigma \sim d^{0.5}$ (Larson 1981)
- Indicates turbulence important throughout molecular ISM
- Also part of evidence that many molecular clouds are self-gravitating and in virial equilibrium

Size-linewidth relation for 230 molecular clouds
In the Milky Way (Solomon et al. 1987) (mid-galaxy $3<R<10$ kpc)
modern size-linewidth relation for Milky Way molecular clouds shows more variation in cloud properties

inner galaxy $R < 1 \text{kpc}$ (gold)
outer galaxy $R > 10 \text{kpc}$ (black)
mid-galaxy $3 < R < 10 \text{kpc}$ (blue, red)

Heyer & Dame 2015

- size-linewidth relation not uniform throughout galaxy
  (Larson’s ‘Law’ not obeyed by all clouds!)
- some clouds not virialized
if clouds obey virial theorem:

\[ \langle v^2 \rangle = \frac{GM}{r} \]

\[ \sigma_v^2 = \langle v^2 \rangle \sim \frac{GM}{r} \sim \frac{G\Sigma r^2}{r} \sim G\Sigma r \]

since \( \Sigma = \frac{M}{r^2} \)
Molecular Clouds in outer Milky Way have weaker CO emission.

Part of this is a lower mass surface densities of clouds, but part might also be a different CO-H$_2$ relation.
CO-H$_2$ relationship not universal!

- X factor depends on n$^{1/2}$/T in best(?) case of optically thick CO over whole H$_2$-dominated region of self-gravitating gas cloud
- At low metallicity (Z$<\sim$0.5$Z_{\text{sun}}$), optically thick CO covers only small part of H$_2$-dominated region of gas cloud (CO only in “cores”) $\rightarrow$ CO not good H$_2$ tracer in low mass galaxies
- Not all molecular gas in self-gravitating clouds $\rightarrow$ some “diffuse” molecular gas with high L(CO)/M(H$_2$)
- Cloud shadowing: clouds which overlap in space & velocity will be hidden
Main molecular lines observed in other galaxies

- \( \text{CO} = ^{12}\text{CO} \) is brightest line, traces gas with densities \( \sim 10^3 \text{ cm}^{-3} \)
- CO(1-0) lowest transition, easiest to excite at low temperatures
- CO(2-1), CO(3-2), CO(4-3), etc. higher rotational transitions, trace hotter gas; ratios give information on gas temperature
- \(^{13}\text{CO} \) and \(^{18}\text{O} \) more optically thin than \(^{12}\text{CO} \); gives information on optical thickness (& therefore on diffuse gas)
- HCN, HCO+ (\( 10^5 \text{ cm}^{-3} \)); CS (\( 10^4 \text{ cm}^{-3} \)) trace gas with higher densities; together with CO gives information on gas density
other way to estimate $H_2$ masses from molecular line observations

- observe optically thin species (e.g. $C^{18}O$) in several different transitions
- determine column density of that molecule along the line-of-sight, e.g. $N(C^{18}O)$
- adopt your best guess for the $N(C^{18}O)/N(H_2)$ ratio to get $N(H_2)$
CO map of Milky Way

Figure 3
An image of $^{12}$CO $J = 1-0$ emission constructed from the recent Center for Astrophysics campaign to examine the high-latitude sky and the composite surveys of Dame et al. (2001) and Mizuno & Fukui (2004).

Heyer & Dame 2015
Vertical distributions of CO in spirals

- NGC 891 is edge-on Sb similar to Milky Way

- Vertical scale heights

  \[
  \text{MW(sol neigh) N891 (R>1 kpc)} \\
  \text{CO} \quad 50 \text{ pc} \quad 100 \text{ pc} \\
  \text{OB *’s} \quad 50 \text{ pc} \\
  \text{FG *’s} \quad \text{few 100 pc}
  \]

- Molecular gas is thinnest disk component. Newly formed stars have same scale height as molecular clouds in which they form

- As stars age, they “heat up” and increase their scale height

- Molecular gas scale height likely smaller near galaxy centers (thinner disks near center)
Radial distributions of CO vs. stars

Similar radial distributions on average, but more structure in CO than stars

In central ~1-2 kpc (or “bulge” region), some galaxies have lots of molecular gas, others have relatively little

Regan et al 2001
BIMA SONG
Radial distribution of $H_2$ in Milky Way (from $R=3$-16 kpc)

for $R<8$ kpc, $M(H_2) \sim M(HI)$
for $R>8$ kpc, $M(H_2) \ll M(HI)$
Milky Way radial gas distributions

new calibration of CO: H$_2$ should be $\sim$3 x lower!

circumnuclear gas concentration in central $\sim$1 kpc

bar region

Scoville 2012
HI vs H$_2$ radial distributions in spirals

H$_2$ “fills in” central plateau or hole in HI in 4 of these spirals; central depression in both HI & H$_2$ in one of these spirals

Kenney & Young 1989
CO vs. other radial distributions in spirals

- CO radial distributions most similar to tracers of massive star formation (i.e. Ha, FIR, radio continuum)
- CO radial distribution similar to disk starlight in many cases -> evidence that stellar disk is exponential because it formed from exponential gas disk (dissipation & angular momentum transport?)
- Central HI “hole” or depression or plateau filled in with molecular gas (H₂) in many (but not all) galaxies
- Some galaxies have relative lack of CO in center, roughly coincident with bulge
Stellar disks are thin and exponential because they form from gas disks that are thin and \( \sim \)exponential, due (in part) to gas dissipation.

Stellar bulges are fat and \( r^{1/4} \) because they form from star systems that reach equilibrium without dissipation.
CO mapping of grand design spiral M51

Combined interferometer & single dish data → get good resolution & include all flux
Spiral structure in CO & other tracers in M51

Young stars (HII regions) located downstream from CO peak in some parts of spiral arm indicates time sequence for star formation

Large arm-interarm contrast (~3:1) in CO: many molecular clouds form in spiral arms

Fig. 4. a–d. The $^{12}$CO(2–1) emission I(CO) (Contours as in Fig. 2) overlaid on (grey scales): a red continuum photograph, b Hα CCD image, c 21-cm radio-continuum nonthermal and d 6-cm thermal emissions. The radio-continuum thermal and non-thermal maps are smoothed to a resolution of 12".
Galaxy centers: Gas responds strongly to stellar bars

M101 has weak stellar bar
Molecular gas has strong response, piles up along leading edge of bar
Gravitational torques can drive gas inwards
CO in strongly Barred Galaxies

NGC 7479 BVR image

NGC 7479 CO on J-K

CO peaks lies on dust lane at leading edge of stellar bar

CO and Ha gas kinematics
Laine et al 1999

Large velocity jump (100-200 km/s) across the bar!! Dense gas piles up due to shock at leading edge of bar

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Circumnuclear Star Formation in Spiral Galaxies

- Star-forming ring deep inside bar at $r=6''=300$pc in NGC 3351

NGC 3351  
M95  
D=10 Mpc

BVR Herschel Telescope  Knapen
Very Different Distributions of Gas and Young Stars in “non-starburst” NGC 3351

molecular gas exists both **inside and outside** of star forming ring & within the ring is **concentrated at 2 ends**

CO(1-0) 2” OVRO Jogee+05
Molecular Gas Properties of Galaxies

How much molecular gas?
In which ISM phase is most of the gas mass?
M(H$_2$) vs. M(stellar) in massive nearby galaxies

![Graph showing M(H$_2$) vs. M(stellar) in massive nearby galaxies.]

- **COLD GASS CO(1-0) survey**
  - 350 nearby galaxies with M(star)$>10^{10}$ $M_\odot$
  - All morphological types

- **Cold gas mass fraction ranges from M(H$_2$)/M(star) <0.01 to 0.20**

- **Average for detected galaxies 0.06**

**Literature compilation:**
- Much larger range than careful dedicated survey suggests large errors for some M(H$_2$) values in literature

**COLD GASS Saintonge et al. 2011**
$M(H_2)/M_{\text{star}}$ vs. key properties in massive nearby galaxies

$M(H_2)/M(\text{star})$ drops for:
- $M(\text{star}) > 10^{11} \ M_{\odot}$
- $\mu(\text{star}) > 10^{8.7} \ M_{\odot} \ \text{kpc}^{-2}$
- $R_{90}/R_{50} > 2.6$

- $E$’s, large bulge
- $SO$’s and $Sa$’s have relatively little cold gas

Correlation between $M(H_2)/M(\text{star})$ and NUV-$r$
- higher cold gas fractions in bluer galaxies (which have higher SFRs)

COLD GASS
Saintonge et al 2011
M(H$_2$) vs. M(HI) in massive nearby galaxies

M(H$_2$)/M(HI) varies by 2(+) orders of magnitude in massive galaxies,
Range: M(H$_2$)/M(HI) <0.03 to >3
trends with stellar mass, color, etc are very weak
(so hard to predict...)

COLD GASS
Saintonge etal 2011
Molecular Gas Properties of Galaxies

How much molecular gas?
In which ISM phase is most of the gas mass?

• $M(H_2)/M(HI) \sim 0.1-3$ for nearby spirals, less for many E’s and S0’s

• $M(HI+H_2)/M(\text{stars}) \sim 0.01-0.30$ for nearby spirals
  (generally higher in galaxy centers, low mass late type galaxies, mergers,
  young galaxies; generally lower for E’s and S0’s)

• $L(\text{CO})/M(HI)$ and $L(\text{CO})/M(\text{stars})$ lower in low-mass (dwarf)
galaxies
  May be due to different X (lower metallicity) or lower $M(H_2)/M(HI)$ -- it is probably both!
one of main ways that galaxies evolve is by converting gas into stars → the star formation rate (SFR) is one of the most important measures of galaxy evolution

How can we measure the SFR in galaxies?
How can we measure the rate of star formation in galaxies?

**main approach:** observe radiation from stars that *must be young* (it is hard to estimate ages of stars!)

use massive stars:

- *massive stars don’t live long, so every one must be young*
- *massive stars are hot & luminous, so they produce lots of UV radiation*
main sequence lifetime of star $\tau_{MS}$

$$\tau_{MS}(M) \sim \left( \frac{M}{M_{\text{sun}}} \right)^c \tau_{\text{sun}}$$

$$\tau_{MS}(M) \sim 10^{10} \left( \frac{M}{M_{\text{sun}}} \right)^c \text{ yrs}$$
Main sequence lifetime of star $\tau_{MS}$

$$\tau_{MS}(M) \sim (M/M_{sun})^{-2.5} \tau_{sun}$$

$$\tau_{MS}(M) \sim 10^{10} (M/M_{sun})^{-2.5} \text{ yrs}$$

This is an approximation which is a bit off for the most massive and least massive stars.

Lifetime of $10 \, M_{sun}$ star is $10^7$ years.
Only blackbodies hotter than $T>20,000\text{K}$ emit significant quantities of Lyman continuum UV photons $(E>13.6 \text{ eV}, \lambda<0.0912 \mu\text{m})$ ionize H atoms.

Lyman continuum UV photons $(E>13.6 \text{ eV}, \lambda<0.0912 \mu\text{m})$ ionize H atoms.

OB stars have $T>20,000\text{K}$

Main sequence (MS) stars have large luminosity

White dwarfs hot enough but small size means small luminosity

MS OB stars don’t live long so any MS OB star is young & therefore formed recently
Counting Lyman continuum photons to estimate massive star formation rates

Basic idea: Lyman continuum photons (extreme ultraviolet photons, $\lambda<91.2\text{nm}$) in galaxies are produced (mostly) by hot young massive stars which live for such a short time that every one we see must have formed recently.
\[ N_{\text{Ly}}(\text{tot}) = \dot{N}(>10 \, M_{\odot}) \int_{10}^{M_u} \Psi(M) \, N_{\text{ly}}(M) \, \tau_{\text{MS}}(M) \, dM \]

where:

- \( N_{\text{Ly}}(\text{tot}) = \) total # Lyman continuum photons from galaxy
- \( \dot{N}(>10 \, M_{\odot}) = \) stellar birthrate (stars born per year) for stars with \( M>10 \, M_{\odot} \) (only ones that emit LyC photons)
- \( N(M) = \int_{M_1}^{M_2} \Psi(M) \, dM \) \#stars formed with masses between \( M_1 \) and \( M_2 \)
- \( \Psi(M) = dN/dM = \text{IMF} = \) initial mass function (# stars formed per unit mass interval)
- \( N_{\text{ly}}(M) = \) Lyman continuum photon rate for star of mass \( M \)
- \( \tau_{\text{MS}}(M) = \) main sequence lifetime of star
- \( M_u = \) upper mass "cutoff" (most massive stars which form)
**Lyman continuum photon rate**

\[
N_{\text{Ly}(\text{tot})} = N(>10 \, M_{\odot}) \frac{\int_{10}^{M_u} N(M) \, N_{\text{Ly}}(M) \, \tau_{\text{MS}}(M) \, dM}{\int_{10}^{M_u} N(M) \, dM}
\]

where:

- \(N_{\text{Ly}(\text{tot})}\) = total # Lyman continuum photons from galaxy
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- \(\tau_{\text{MS}}(M)\) = main sequence lifetime of star
- \(M_u\) = upper mass “cutoff” (most massive stars which form)
Lyman continuum photon rate

- relation for Lyman continuum photon rate assumes that there are enough individual massive stars at any one time that we can treat problem statistically by weighing the contribution from each star by its lifetime and abundance relative to stars of different masses.

- this is OK for most late type galaxies which have 100’s-1000’s of massive stars, but approach breaks down for smaller numbers (& smaller regions within galaxies).

- also breaks down if SFR (\( \dot{N} \)) has not been constant for last \( \sim 10^7 \) years.
Lyman continuum photon rate per star

\[ N_{\text{ly}}(M) = \text{Lyman continuum photon rate for star of mass } M \]

\[ N_{\text{ly}}(M) = 3.8 \times 10^{42} \left(\frac{M}{M_{\odot}}\right)^{3.86} \quad M > 32 \, M_{\odot} \]

\[ N_{\text{ly}}(M) = 2.4 \times 10^{35} \left(\frac{M}{M_{\odot}}\right)^{8.67} \quad 9 \, M_{\odot} > M > 32 \, M_{\odot} \]

(only appx, Panagia 1973)

\[ N_{\text{ly}}(M) = 2 \times 10^{29} \left(\frac{M}{M_{\odot}}\right)^{21.8 - 5.75 \log(M/M_{\odot})} \quad M > 10 \, M_{\odot} \]

(Tutokov & Krugel 1981)
main sequence lifetime of star $\tau_{MS}$

$\tau_{MS}(M) \sim (M/M_{\text{sun}})^{-2.5} \tau_{\text{sun}}$

$\tau_{MS}(M) \sim 10^{10} (M/M_{\text{sun}})^{-2.5} \text{ yrs}$

this is approximation which is a bit off for the most massive and least massive stars

lifetime of $10 \ M_{\text{sun}}$ star is $10^7 \text{ years}$
initial mass function IMF $\Psi(M)$

\[ N(M) = \int_{M_1}^{M_2} \Psi(M) \, dM \]  
#stars formed with masses between $M_1$ & $M_2$

$\Psi(M) = \frac{dN}{dM} = IMF = initial \ mass \ function \ (one \ way \ to \ define)$

\[ \frac{dN}{dM} = \Psi(M) \sim M^{-\alpha} \quad \text{one \ way \ to \ define \ IMF} \]

\[ \frac{dN}{d\log M} \sim M^{-\gamma} \quad \alpha = \gamma + 1 \quad \text{another \ way \ to \ define \ IMF} \]

Salpeter (1955) \quad \alpha = -2.35 \quad \text{historical}

Kroupa & Weidner (2003) \quad \alpha = -2.35 \ \text{for} \ 1-100 \ M_{\odot} \quad \alpha = -1.3 \ \text{for} \ 0.1-1 \ M_{\odot} \quad \text{modern values}

Chabrier (2003) \ similar \ result \ but \ more \ complex \ form
**Lyman continuum photon rate**

\[
N_{Ly}(\text{tot}) = \dot{N}(>10 \, M_{\odot}) \int_{10}^{M_u} \Psi(M) N_{ly}(M) \tau_{MS}(M) \, dM \\
\int_{10}^{M_u} \Psi(M) \, dM
\]

where:

\( N_{Ly}(\text{tot}) \) = total # Lyman continuum photons from galaxy

\( \dot{N}(>10 \, M_{\odot}) \) = stellar birthrate (stars born per year) for stars with \( M>10 \, M_{\odot} \) (only ones that emit LyC photons)

\( N(M) = \int_{M_1}^{M_2} \Psi(M) \, dM \) #stars formed with masses between \( M_1 \) and \( M_2 \)

\( \Psi(M) = \frac{dN}{dM} = \text{IMF} = \text{initial mass function} \)

\( \# \text{ stars formed per unit mass interval} \)

\( N_{ly}(M) \) = Lyman continuum photon rate for star of mass \( M \)

\( \tau_{MS}(M) \) = main sequence lifetime of star

\( M_u \) = upper mass “cutoff” (most massive stars which form)
relating LyC rate to birthrate to MSFR to SFR

relate SFR (in $M_{\text{sun}} \text{ yr}^{-1}$) to birthrate (in #stars yr$^{-1}$)

\[
\text{SFR} = N \langle M \rangle \quad \text{where} \quad \langle M \rangle = \frac{\int_{M_L}^{M_U} \Psi(M) M \, dM}{\int_{M_L}^{M_U} \Psi(M) \, dM}
\]

\[
\text{MSFR} (M>10 \, M_{\text{sun}}) = 1.2 \times 10^{-54} \, N_{Ly}(\text{tot}) (M_{\text{sun}} \text{ yr}^{-1}) \quad (\text{photons sec}^{-1})
\]

\[
\text{assumes: Kroupa IMF, more accurate form of } N_{Ly}(M), \text{ solar metallicity for all stars } (N_{ly} \sim Z^{-0.4}); \text{ this is average over } 10^7 \text{ yrs, lifetime of } 10 \, M_{\text{sun}} \text{ star}
\]

\[
\text{SFR(tot)} = \text{constant} \times \, \text{MSFR} (M>10 \, M_{\text{sun}})
\]
relating LyC rate to birthrate to MSFR to SFR

Relate SFR (in $M_{\odot}$ yr$^{-1}$) to birthrate (in #stars yr$^{-1}$)

$$SFR = N \langle M \rangle$$

where

$$\langle M \rangle = \frac{\int_{M_L}^{M_U} \Psi(M) M dM}{\int_{M_L}^{M_U} \Psi(M) dM}$$

$$MSFR (M>10 M_{\odot}) = 1.2 \times 10^{-54} N_{Ly}(tot)$$

$$(M_{\odot} \text{ yr}^{-1}) \quad \text{(photons sec}^{-1})$$

Kennicutt & Evans 2012

assumes: Kroupa IMF, more accurate form of $N_{Ly}(M)$, solar metallicity for all stars ($N_{ly} \sim Z^{-0.4}$); this is average over $10^7$ yrs, lifetime of 10 $M_{\odot}$ star

$$SFR(tot) = 6.3 \times MSFR (M>10 M_{\odot})$$

for Kroupa IMF
relating LyC rate to birthrate to MSFR to SFR

relate SFR (in \( M_{\text{sun}} \text{ yr}^{-1} \)) to birthrate (in \#\text{stars yr}^{-1})

\[
\text{SFR} = N \langle M \rangle \quad \text{where} \quad \langle M \rangle = \frac{\int_{M_L}^{M_U} N(M) M \, dM}{\int_{M_L}^{M_U} N(M) \, dM}
\]

\[
\text{MSFR (M}>10 \ M_{\text{sun}}\) = 1.2 \times 10^{-54} \ N_{\text{Ly}}(\text{tot}) \quad (M_{\text{sun}} \text{ yr}^{-1}) \quad (\text{photons sec}^{-1})
\]

Kennicutt & Evans 2012

assumes: Kroupa IMF, more accurate form of \( N_{\text{Ly}}(M) \), solar metallicity for all stars \( (N_{\text{Ly}} \sim Z^{-0.4}) \); this is average over \( 10^7 \) yrs, lifetime of \( 10 \ M_{\text{sun}} \) star

\[
\text{SFR(tot)} = 6.3 \ \text{MSFR (M}>10 \ M_{\text{sun}}\) \quad \text{for Kroupa IMF}
\]
most of stellar mass is in low mass stars!

\[ \text{SFR(tot)} = 6.3 \ \text{MSFR} (M>10 \ M_{\odot}) \]

→most of gas mass consumed by star formation goes into low mass stars which are not easily observable!

→correction factor to get from MSFR to SFR is large and depends on IMF, which is very hard to measure in other galaxies
We can’t directly measure most of the Lyman continuum photons produced in galaxies!

Lyman continuum photons (\(\sim 50 \text{nm} < \lambda < 91.2 \text{nm}\)) are those which easily ionize H atoms (absorption cross-section \(\sim \lambda^3\)). There are so many H atoms in space & the absorption cross-section is so large that these photons rarely escape the galaxy.
Estimating SFRs in Galaxies

I. Lyman UV continuum ($\lambda<91.2$nm)
   A. recombination lines (e.g. H$\alpha$)
   B. thermal radio continuum

II. UV continuum ($91.2$nm $<\lambda<280$nm)

III. Far-Infrared continuum

IV. Non-thermal radio continuum

Multi-wavelength observations – combine different tracers to achieve greater accuracy