Physics 235

Extragalactic Astrophysics
Prof. Crystal Martin
Star Formation & Chemical Evolution

• Please start reading ch. 9; slides available on website.

• Outline
  – Introduction: A Separable Problem
  – Properties, Dynamical State, and Formation of Molecular Clouds
  – Star Formation Efficiency
  – Initial Mass Function (ch 9)
  – Star Formation Laws (ch 9)
  – Star Formation Diagnostics (ch 10)
  – Star Formation & Chemical Evolution (ch 10)
  – Chemical Evolution (ch 10)
Star Formation in Galaxies. Resources

- Chapter 9 of MvBW
- The Relationship between Gas Content and Star Formation in Molecular-rich Spiral Galaxies, Wong, Tony; Blitz, Leo, 2002ApJ...569..157W
- The Global Schmidt Law in Star-forming Galaxies, Kennicutt, Robert C., Jr., 1998ApJ...498..541K
- Star Formation Thresholds in Galactic Disks, Martin, Crystal L.; Kennicutt, Robert C., Jr., 2001ApJ...555..301M
- The Star Formation Law in Nearby Galaxies on Sub-Kpc Scales, Bigiel, F.; Leroy, A.; Walter, F.; Brinks, E.; de Blok, W. J. G.; Madore, B.; Thornley, M. D, 2008AJ....136.2846B
- A general model for the CO-H2 conversion factor in galaxies with applications to the star formation law, Narayanan, Desika; Krumholz, Mark R.; Ostriker, Eve C.; Hernquist, Lars, 2012MNRAS.421.3127
Star Formation in Galaxies. Resources

Introduction
How Do We Measure the Star Formation Rate of a Galaxy?

- We count the number of recently formed stars.
- And we know all massive stars formed recently.
Hα, Paα, 8µm, 24µm
Sites of Star Formation in Spiral Galaxies
Figure 1. $X_{\text{CO}}$ versus mass-weighted mean metallicity (in units of solar) for all $z = 0$ model galaxies with $\Sigma_{\text{H}_2} \sim 100$ M$_{\odot}$ pc$^{-2}$. The contours represent the number of snapshots in a given $X_{\text{CO}}-Z'$ bin, with the numbers increasing with increasing lightness of the contour. The dashed line outer contour encompasses all model galaxies, regardless of their gas surface density. Overlaid are observational data points from Bolatto et al. (2008), Leroy et al. (2011) and Genzel et al. (2012). The solid line shows our best fit to the simulations and is expressed in equation (8) and described in Section 4.
SFR / Area = dΣ*/dt = (2.5 ± 0.7) × 10^{-4} \ M_0/yr/kpc^2 \ (\ Σ_{\text{gas}} / 1 \ M_0 \ pc^{-2} )^{1.4±0.15}

Note: A linear relationship has been shown relative to Σ(H_2).
A Separable Problem...

• We must understand the formation of GMCs.
• We must understand why a GMC is inefficient at turning gas into stars.
Properties of GMCs
Observed Mass Distribution of GMCs. I. Milky Way

- Compare $dN/dM \sim M^{-1.3}$ to $M^{-1.9}$ stellar initial mass function.
- Most clouds are low mass but most of the molecular gas in in the most massive clouds.
- A $10^5$ Msun cloud contains on average one O star.
- A $10^6$ Msun cloud takes $3 \times 10^7$ year to photoevaporate.
Observed Mass Distribution of GMCs. II. Local Group

- $dN/dM \sim M^{-1.5}$ in the inner MW
- $dN/dM \sim M^{-2.1}$ and $M^{-2.9}$ in outer MW and M31
- So there appear to be systematic differences with environment.

Fig. 2.—Mass distribution of the SRBY virial mass measurements. A truncated power-law fit to the data using the methods of this study is shown as a solid line. The data show a significant break around $N = 50$, and the fit recovers this feature well.
Formation of $H_2$
Timescales for Molecule Formation & Destruction

• Via recombination of pairs of adsorbed H atoms on the surface of dust grains. Dust-to-gas mass ratio is typically 1:100.

\[ t = 1.5 \times 10^7 \text{ yr} \ (100 \ \text{cm}^{-3} / n) \]

• Much less efficient without the dust. Gas-phase reactions important for Pop III stars.

• Photodissociation destroys molecules. In average interstellar radiation field, a hydrogen molecule lives \( \sim 600 \text{ yr} \). Interiors of GMCs are shielded from this radiation.

• Molecular hydrogen forms where external pressure is high and the radiation field is low.

• Define the molecular-to-atomic ratio

\[ R_{\text{mol}} = \frac{n(H_2)}{n(\text{HI})} \]

• Calculations show \( R_{\text{mol}} \sim P^{2.2} \text{ J}^{-1} \), where \( j \) is the specific intensity of the radiation field (Elmegreen 1993).
Molecular Fraction in Gas Disks

\( \frac{1}{R_{\text{mol}}} \)

\( \log \left( \frac{\Sigma_{\text{H}_2}/\Sigma_{\text{mol}}}{P} \right) \)

\( \log \left( \frac{P}{k_B} \right) \text{ [cm}^{-3}\text{ K]} \)

\( \propto P^{-0.8} \)
Pressure in Gas Disks

• Gas disk is in hydrostatic equilibrium (vertical direction)
  \[ P \approx \frac{\pi}{2} G \Sigma_{\text{gas}} \left[ \Sigma_{\text{gas}} + \left( \frac{\sigma_{\text{gas}}}{\sigma_*} \right) \Sigma_* \right] \]

• Define the molecular fraction
  \[ f_{\text{mol}} = \frac{\Sigma (H_2)}{\Sigma_{\text{gas}}} \]

• Consider the outer disk where the molecular fraction is low.
  – We have \( n(\text{HI}) \approx n(H) \), so \( f_{\text{mol}} \approx R \).
  – Then \( R_{\text{mol}} \sim P^{1.1} / (\Sigma_{\text{gas}})^{0.5} \)
  – And \( P \approx \frac{\pi}{2} G \Sigma_{\text{gas}} \left[ \Sigma_{\text{gas}} \right] \)
  – So \( R_{\text{mol}} \sim P^{0.85} \), which agrees well with the observations.
Regulation of the Star Formation Rate. II.

What processes determine whether GMCs form?

Popular ideas include …

Ability to form molecular gas?

Gravitational Instability?

Shear Instability?
Toomre Stability Criterion

- Differential rotation makes perturbations in a disk subject to coriolis forces, which resist collapse. The Jeans Criterion no longer describes instability.
- Toomre $Q = \sigma \kappa / (3.36 \, G \, \Sigma_{\text{gas}})$
- Epicyclic frequency $\kappa = \sqrt{2} \, \frac{V_c}{R (1 + \frac{R}{V_c} \frac{dV_c}{dR})^{1/2}}$
- If $Q < 1$, then perturbations at the critical wavelength will collapse. The critical wavelength is roughly 1 kpc, corresponding to mass scales $\sim 1\,\text{e}^7 \, \text{M}_\odot$.
- GMCs are smaller than this scale, so the role of gravitational instability is debated. It is possible that gravitational instability sets off subsequent thermal instability.
Sites of Star Formation in Spiral Galaxies
Kennicutt – Schmidt Law

\[ \frac{M_{\text{gas}}}{\text{SFR}} \sim 10^9 \text{ yr} \left(\frac{100}{\Sigma_{\text{gas}}}\right)^{0.5} \gg \text{Free-fall timescale (few x } 10^6 \text{ yr)} \]

**Fig. 6.**—Composite star formation law for the normal disk (filled circles) and starburst (squares) samples. Open circles show the SFRs and gas densities for the centers of the normal disk galaxies. The line is a least-squares fit with index \( N = 1.40 \). The short, diagonal line shows the effect of changing the scaling radius by a factor of 2.

**Fig. 7.**—Relation between the SFR for the normal disk and starburst samples and the ratio of the gas density to the disk orbital timescale, as described in the text. The symbols are the same as in Fig. 6. The line is a median fit to the normal disk sample, with the slope fixed at unity as predicted by equation (7).
Which Component of Gas?

Figure 4. $\Sigma_{\text{HI}}$ as a function of $\Sigma_{\text{HI}}$ (left), $\Sigma_{\text{H}_2}$ (middle), and $\Sigma_{\text{tot}} = \Sigma_{\text{HI}} + \Sigma_{\text{H}_2}$ (right) in our sample galaxies at 750 pc resolution. Each panel shows results for one galaxy. Green, orange, red, and magenta cells show contours of 1, 2.5, and 10 independent data points, respectively, per 0.05 dex-wide cell (for $\text{H}_2$ in NGC 4736 we use a scatter plot due to the low number of sampling points). The crosses show spatial measurements over tilted rings from the radial profiles. The diagonal dotted lines show lines of constant SHE, indicating the level of $\Sigma_{\text{HI}}$ needed to consume 1%, 10%, and 100% of the gas reservoir (including helium) in 10^7 years. Thus, the lines also correspond to constant gas depletion times of, from top to bottom, 10^9, 10^8, and 10^13 yr. Dashed vertical lines in the $\text{H}_2$ (left) and total gas (right) plots show the surface density where the $\text{H}_2$ saturates (see Section 3.3). Dotted vertical lines in the middle plots show the typical sensitivity for our CO data. We show OLS bisector fits to the $\text{H}_2$ and total gas data with a solid line and quote the results.
The efficiency of star formation is lower in the outer parts of spiral galaxies.

Figure 10. $\Sigma_{\text{SFR}}$ vs. $\Sigma_{\text{gas}}$ for the spiral galaxies with data colored according to the galactocentric radius. Every data point represents one sampling point; the data are the same as in the middle-right plot of Figure 8. We show the normalized galactocentric radius of every sampling point via its color, where, in units of $r_{25}$, the colors correspond to black < 0.25, red 0.25–0.5, orange 0.5–0.75, and green > 0.75. The diagonal dotted lines and all other plot parameters are the same as in Figure 4. The data clearly break up according to galactocentric radius, with low SFE/high gas depletion time points corresponding to the outer parts of the spirals.

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Empirical Star Formation Laws

• Kennicutt-Schmidt Law: Averaged over star-forming disk
  \[ \text{SFR / AREA (M}_0/\text{yr/kpc}^2) = (\Sigma_{\text{gas}} / M_0 \text{ pc}^{-2})^{1.4} \]

• Looks like SF is controlled by self-gravity, where
  \[ \text{SFR} = (\text{efficiency}) \times \rho_{\text{gas}} / t_{\text{ff}}, \text{ since } t_{\text{ff}} \sim \rho_{\text{gas}}^{-1/2} \]

• Taking the dynamical timescale at the edge of the star-forming disk, however, we see that
  \[ \text{SFR /AREA} = 0.017 \Sigma_{\text{gas}} \Omega \]

• **Only 10% of the gas in consumed in an orbit.** (Compare to the SFE per GMC, which we found was \(~0.002.\))