Star Formation on Galactic Scales

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Outline

- Observation method overview.
  - How to measure star formation rate (SFR).
  - How to measure gas density in various phases.
- Observational results.
  - Disk-averaged.
  - Spatially-resolved.
- Theoretical efforts.

Empirical Relations

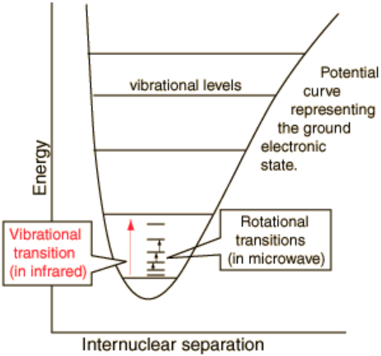
- A few empirical relations are found to fit the data well.
  - $\Sigma_{\rm SFR} = A\Sigma_{\rm gas}^{N}$ (Kennicutt & Schmidt Law)
  - $\Sigma_{\rm SFR} = A\frac{\Sigma_{\rm gas}}{t_{\rm dyn}}$
  - $\Sigma_{\rm SFR} \propto \eta P_{\rm total}$
- How do we measure these quantities?

Measuring Gas Density

- Atomic Gas.
  - HI spin-flip hyperfine transition.
  - $\lambda = 21\mathrm{cm}$, $\nu = 1.42\mathrm{GHz}$
  - $M_{\mathrm{HI}} = 2.343 \times 10^5 M_\odot (1+z)(\frac{D_L}{\mathrm{Mpc}})^2(\frac{\int F_\nu dv}{\mathrm{Jy\ km\ s^{-1}}})$
- Molecular Gas.
  - H_2 does not emit strongly.
  - Use other trace molecules, most commonly CO.
  - $X_{\mathrm{CO}} = \frac{N(\mathrm{H_2})}{\int T_A dv} = 1.58 \times 10^{20} n_3^{1/2}(e^{5.5\mathrm{K}/T_{\mathrm{exc}}})\frac{\mathrm{cm^{-2}}}{\mathrm{K\ km\ s^{-1}}}$
  - Various issues:
    - CO line is optically thick
    - X_{CO} varying.

Why does H_2 not emit strongly?

- Common interpretation: Lack of electric dipole.
- Actually: Small moment of inertia → Large energy gap → Not populated.
- mass ∼ 15 times smaller, size ∼ 50% smaller.
- $E = \frac{J(J+1)\hbar^2}{2I}$ where $I = \mu r^2$.



http://hyperphysics.phy-astr.gsu.ed

Measuring Star Formation Rate

- Various ways, each have different issues and are sensitive to different timescales.
  - Star count.
  - Ultraviolet.
  - Emission lines.
  - Infrared.
  - X-ray.
  - Radio.

Measuring Star Formation Rate: Star-count

- With complete data of individual stars in a group and good stellar evolution model, one can model everything.
- $\langle \dot{M}_* \rangle = \sum_{M_*=M_l}^{M_u} N(M_*, t_*) M_*/t_*$
- Problems:
  - Need very high quality data.
  - Resolution limit. Not possible outside local group.

Measuring Star Formation Rate: UV & IR

- UV
  - Emitted by young stars.
  - Main database is GALEX.
  - Issue: Dust.
- IR
  - Emitted by dust cloud surrounding young stars
  - Various database (WISE, Spitzer, Herschel, Planck)
  - Issue: Lack of dust.
- Complementary to each other.

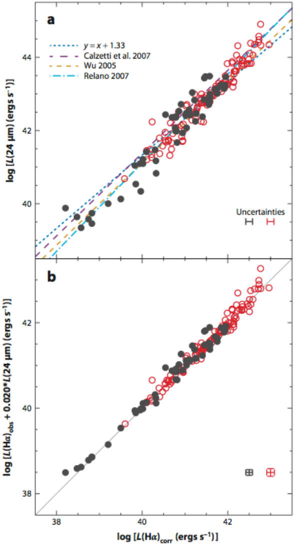
Measuring Star Formation Rate: Emission Lines

- Emission lines are associated with HII regions.
- Commonly used lines:
  - Hα (Line of choice).
  - [OII]λ3727.
  - Lyα.
  - Paschen Series.
  - metal IR cooling lines.
- Problems:
  - Dust.
  - Calibration.

Measuring Star Formation Rate: X-ray & Radio

- Both X-ray and radio emissions are associated with young phase of stellar evolution.
  - X-ray: X-ray binary, supernovae & remnants, young stars.
  - Radio: free-free from HII region, synchrotron from supernova remnants.
- Problem: AGNs also emit X-ray and radio wave.

Measuring Star Formation Rate: Combination



Kennicutt & Evans (2012)

Measuring Star Formation Rate: Calibration

Table 1 Star-formation-rate calibrations

Band	Age range (Myr)[a]	L_x units	log C_x[b]	$\dot{M}_*/\dot{M}_*$(K98)[c]	Reference(s)
FUV	0-10-100	ergs s^{-1} (νL_ν)	43.35	0.63	Hao et al. (2011), Murphy et al. (2011)
NUV	0-10-200	ergs s^{-1} (νL_ν)	43.17	0.64	Hao et al. (2011), Murphy et al. (2011)
Hα	0-3-10	ergs s^{-1}	41.27	0.68	Hao et al. (2011), Murphy et al. (2011)
TIR	0-5-100[d]	ergs s^{-1} (3–1100 μm)	43.41	0.86	Hao et al. (2011), Murphy et al. (2011)
24 μm	0-5-100[d]	ergs s^{-1} (νL_ν)	42.69		Rieke et al. (2009)
70 μm	0-5-100[d]	ergs s^{-1} (νL_ν)	43.23		Calzetti et al. (2010b)
1.4 GHz	0-100	ergs s^{-1} Hz^{-1}	28.20		Murphy et al. (2011)
2–10 keV	0-100	ergs s^{-1}	39.77	0.86	Ranalli et al. (2003)

Kennicutt & Evans (2012)

Observables → Theoretical Quantities

Theory	Form	Observables
	Star Formation Laws	
Disk free-fall time		
. . . fixed scale height	$\text{SFE} \propto \Sigma_{\text{gas}}^{0.5}$	Σ_{gas}
. . . variable scale height	$\text{SFE or } R_{\text{mol}} \propto \frac{\Sigma_{\text{gas}}}{\sigma_{\text{g}}}\left(1+\frac{\Sigma_*}{\Sigma_{\text{gas}}}\frac{\sigma_{\text{g}}}{\sigma_{*,z}}\right)^{0.5}$	$\Sigma_{\text{gas}}, \Sigma_*, \sigma_g, \sigma_*$
Orbital timescale	$\text{SFE or } R_{\text{mol}} \propto \tau_{\text{orb}}^{-1} = \frac{v(r_{\text{gal}})}{2\pi r_{\text{gal}}}$	$v(r_{\text{gal}})$
Cloud–cloud collisions	$\text{SFE} \propto \tau_{\text{orb}}^{-1} Q_{\text{gas}}^{-1}(1-0.7\beta)$	$v(r_{\text{gal}})$
Fixed GMC efficiency	$\text{SFE} = \text{SFE}(\text{H}_2)\frac{R_{\text{mol}}}{R_{\text{mol}}+1}$	Σ_{H_2}
Pressure and ISM phase	$R_{\text{mol}} \propto (\Sigma_{\text{gas}}(\Sigma_{\text{gas}} + \frac{\sigma_{\text{g}}}{\sigma_{*,z}}\Sigma_*)P_0^{-1})^{1.2}$	$\Sigma_{\text{gas}}, \Sigma_*, \sigma_g, \sigma_*$
	Star Formation Thresholds	
Gravitational instability		
. . . in the gas disk	$Q_{\text{gas}} = \left(\frac{\sigma_g \kappa}{\pi G \Sigma_{\text{gas}}}\right) < 1$	$\Sigma_{\text{gas}}, \sigma_g, v(r_{\text{gal}})$
. . . in a disk of gas and stars	$Q_{\text{stars+gas}} = \left(\frac{2}{Q_{\text{stars}}}\frac{q}{1+q^2} + \frac{2}{Q_{\text{gas}}}R\frac{q}{1+q^2R^2}\right)^{-1} < 1$	$\Sigma_{\text{gas}}, \Sigma_*, \sigma_g, \sigma_*, v(r_{\text{gal}})$
Competition with shear	$\Sigma_{\text{gas}} > \frac{2.5 A \sigma_g}{\pi G}$	$\Sigma_{\text{gas}}, \sigma_g, v(r_{\text{gal}})$
Cold gas phase	$\Sigma_{\text{gas}} > 6.1\ M_\odot\ \text{pc}^{-2} f_{\text{g}}^{0.3} Z^{-0.3} I^{0.23}$	$\Sigma_{\text{gas}}, \Sigma_*, Z, I$

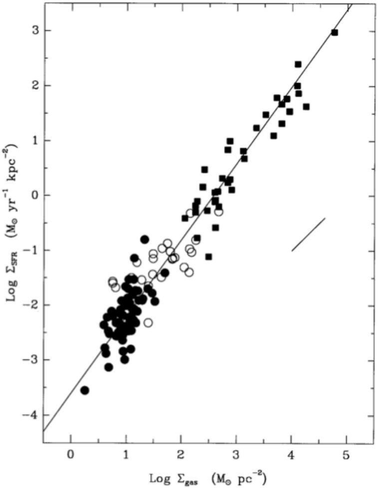
Leroy et al (2008)

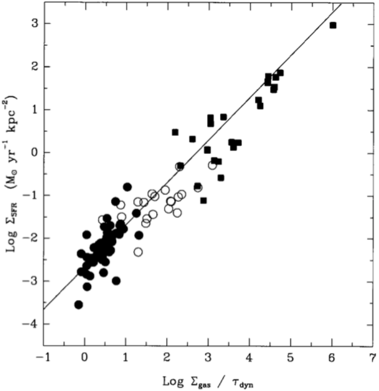
Observational Results

- Apply these methods to measure real galaxies.
- Empirical correlations:
  - $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{1.4}$ (Kennicutt & Schmidt Law)
  - $\Sigma_{\rm SFR} \propto \frac{\Sigma_{\rm gas}}{t_{\rm dyn}}$
  - $\Sigma_{\rm SFR} \propto \eta P_{\rm total}$
- Constrains for theories and high-resolution simulations.
- Used as "subgrid" model for low-resolution simulations.

Observational Results Reviews

- This starts with the prediction by Schmidt (1959) and observation by Kennicutt (1998). The so-called Kennicutt-Schmidt Law.

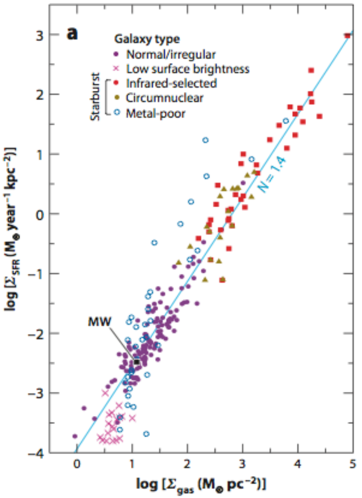




Kennicutt (1998)

More modern dataset

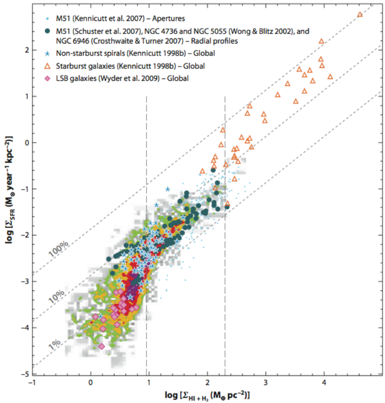
- This game can be played with large galaxy sample.
- Various types and selection methods.
- The correlation still holds.



Kennicutt & Evans (2012)

Resolved KS law

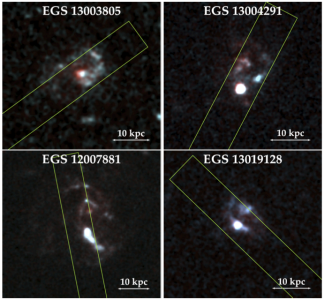
- One can also do this with resolved data.
- Either point-by-point basis, or ring-averaged.
- Some complications on small scale.

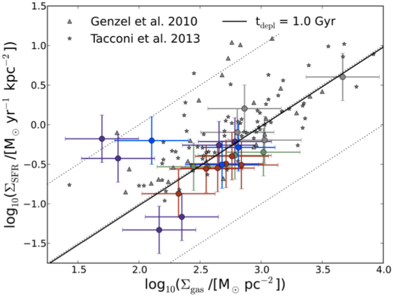


Kennicutt & Evans (2012)

Resolved KS law at high redshift

- Similar result for galaxies at redshift $z \sim 1$ from recent paper.

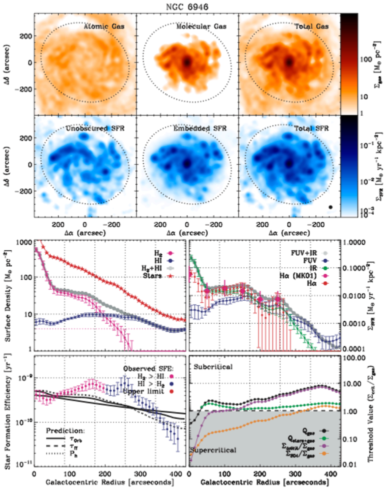




Freundlich et al (2013)

Break in KS law at $\Sigma_{\rm gas} = 10 M_{\odot} pc^{-2}$

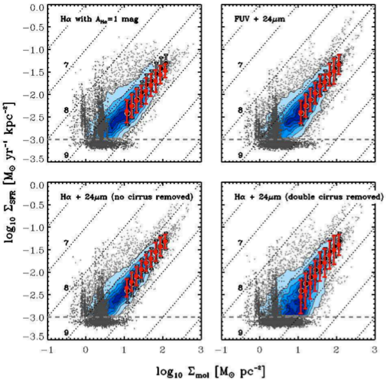
- Break from $N \sim 1.4$ at $\Sigma_{\rm gas} \sim 10 M_{\odot} pc^{-2}$
- Some papers argue that this is associated with gravitational instability scale. However this is not likely the case considering the radial profile.
- This is more likely the sign of second parameter. $\Sigma_{\rm SFR}$ can take any value for $\Sigma_{\rm gas} \sim 10 M_{\odot} pc^{-2}$



Leroy et al (2008)

Break in KS law at $\Sigma_{\rm gas} = 10 {\rm M_\odot pc^{-2}}$

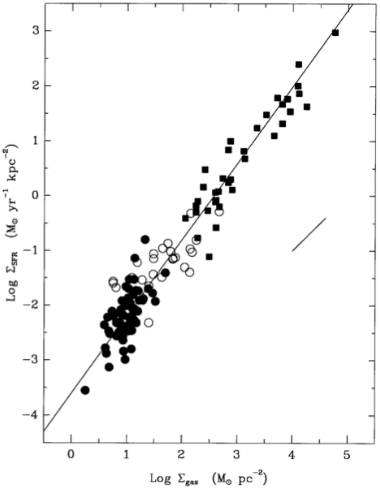
- The correlation with $\Sigma_{\rm mol}$ remains below $10{\rm M_\odot pc^{-2}}$.
- This indicates varying fraction of molecular and atomic gas, as well as the relative importance of gas and stellar potential.



Leroy et al (2013)

Theoretical aspects

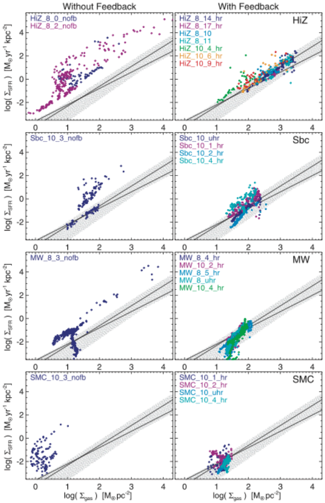
- Challenges for Theorists:
  - Explain the form of empirical relations.
  - Explain the generally low SFR.
  - Naive expectation would be $\Sigma_{\rm SFR} \sim \frac{\Sigma_{\rm gas}}{t_{\rm ff}}$ and this would lead to 2 orders of magnitude higher in SFR.



Kennicutt (1998)

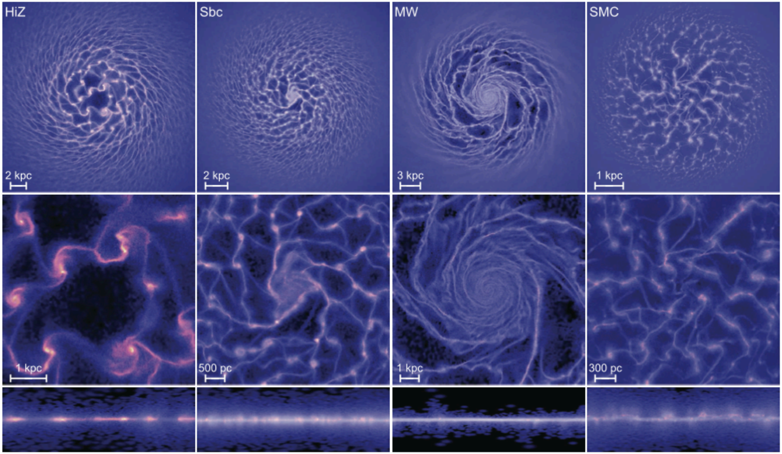
Stellar Feedback

- Sources of feedback: protostellar jets, stellar winds, supernovae and radiation pressure from young star.
- Momentum feedback seems necessary, or the energy is just radiated away easily.
- Hopkins et al (2011) implemented this momentum feedback in simulation and showed that it suppress SF.



Hopkins, Quataert & Murray (2011)

Stellar Feedback

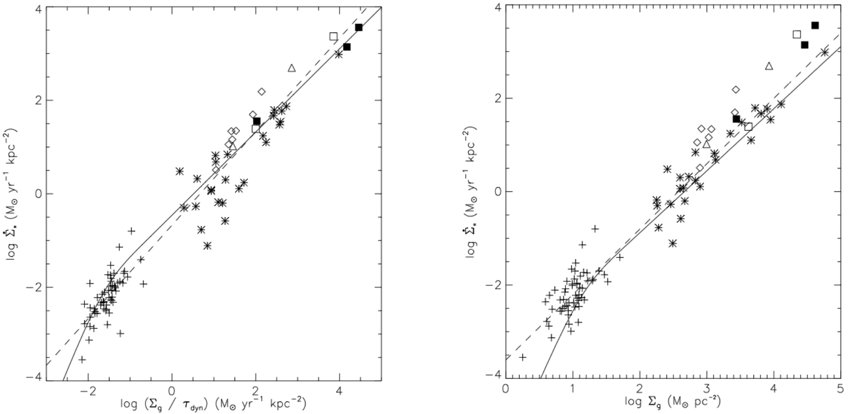


Hopkins, Quataert & Murray (2011)

Turbulence

- Krumholz & McKee (2005) proposed that turbulence-regulated SF can work. This theory is derived from first principle and is based on a few natural assumptions.
  - Clouds are virialized and supersonically turbulent.
  - Density distribution is log-normal.
  - SF happens in dense enough region where gravity is stronger than turbulence.
- Predict the empirical relations found from observation.
- Does not specify the source of turbulence. This turbulence can be due to feedback.

Turbulence



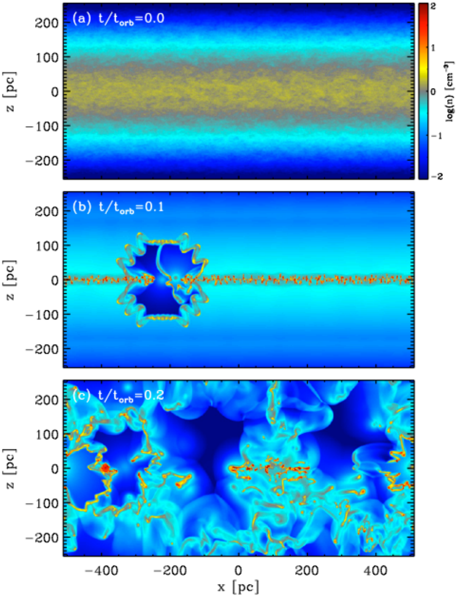
Krumholz & McKee (2005)

Star Formation as Demand

- Traditional thinking: Star formation responds to supply.
  - Gas is the fuel, it collapses and forms stars.
  - Only a few percent of GMC mass is turned into stars.
  - Star formation is very inefficient.
- New way proposed by Ostriker, McKee & Leroy (2010): Star formation responds to demand.
  - In order to keep ISM in equilibrium, energy and turbulence dissipated must be replenished. And pressure must be provided to counter gravity.
  - Star formation is responsible for these processes.
  - To sustain this with a few percent rate, star formation is actually very efficient.

Star Formation as Demand

- A few things have to be balanced
  - Heating vs. Energy loss via radiation.
  - Momentum injection vs. Turbulence dissipation.
  - Pressure vs. Gravity.



Kim, Kim & Ostriker (2011)

Conclusions

- One can learn a lot about galaxies with right measurements.
- Star formation rate in galaxies follows certain empirical relationships.
- These observational results can be used as a test for theories or input for simulations.
- Theories are being developed to explain these observations. None of them is complete yet. But with better dataset, simulations and theories the understanding of this process is advancing quickly.

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