The Star Formation Rate in Multiphase Galactic Disks

thermal & dynamical regulation

Eve Ostriker  U. Maryland
Hiroshi Koyama  Riken
Adam Leroy  NRAO
Christopher McKee  U.C. Berkeley
ISM phases and SF

In galactic disks, the raw material for star formation is the neutral ISM:

• **Atomic gas:**
  – Warm atomic gas \( (T \approx 10^4 \text{ K}; \ n \approx 0.3 \ \text{ cm}^{-3} \text{ in Solar neighborhood}) \)
    diffuse; fills much of volume near Galactic midplane
  – Cold atomic gas \( (T \approx 100 \ \text{ K}; \ n \approx 30 \ \text{ cm}^{-3} \text{ in Solar neighborhood}) \)
    organized in dense clouds, sheets, & filaments; \( L \approx 1-10 \text{ pc} \)
  – Primary component in outer galaxies, but saturated in inner galaxies:
    \( \Sigma_{\text{HI}} \leq 10 \ \text{ M}_\odot \ \text{ pc}^{-2} \) \( (N_H \approx 10^{21} \ \text{ cm}^{-2}) \)

• **Molecular gas:**
  – Cold \( (T \approx 10 \ \text{ K}) \) and dense \( (n > 100 \ \text{ cm}^{-3}) \)
  – Primary component in inner galaxies: \( \Sigma_{\text{H}_2} \) up to \( 10^2-10^3 \ \text{ M}_\odot \ \text{ pc}^{-2} \)

**Observations show increase of** \( \Sigma_{\text{SFR}} \text{ with } \Sigma = \Sigma_{\text{HI}} + \Sigma_{\text{H}_2} \)

• **Superlinear at low, high end** \( (\Sigma \approx \Sigma_{\text{HI}} \leq 10 \ \text{ M}_\odot \ \text{ pc}^{-2}, \ \Sigma \approx \Sigma_{\text{H}_2} \geq 100 \ \text{ M}_\odot \ \text{ pc}^{-2}) \)

• \( \Sigma_{\text{SFR}} = \Sigma_{\text{H}_2} / t_{\text{sf}} \) for \( 10 \ \text{ M}_\odot \ \text{ pc}^{-2} \leq \Sigma \leq 100 \ \text{ M}_\odot \ \text{ pc}^{-2} \)
  with \( t_{\text{sf}} = 2 \times 10^9 \ \text{ yr} \) \( \text{ (Bigiel et al 2008)} \)
Observed $\Sigma_{SFR}$ vs. $\Sigma$

Kennicutt (1998): global Schmidt law for normal and starburst galaxies; $1+p=1.4$

Bigiel et al (2008) local Schmidt law compared to global
Vertically-resolved disk models

- Include:
  - sheared rotation \( V_c = \text{const} \),
  - heating and cooling with bistable thermal equilibrium
  - stellar gravity \( g_z = 4\pi G \rho \ast z \)
  - gas self-gravity
  - HII region feedback: intense local heating
- Explore a range of \( \Sigma_{\text{gas}}, \Omega, \) and \( \rho \ast \)
Temperature and density -- evolution

T

Koyama & Ostriker (2009)
Schmidt laws in vertically-resolved turbulent, multiphase models with $\Omega \propto \Sigma_{\text{gas}}$

Q series: $Q_{\text{gas}}=\text{const}$, $Q_*=\text{const}$

R series: $Q_{\text{gas}}=\text{const}$, $\rho_*=\text{const}$

require $\epsilon_{\text{ff}}=0.001-0.01$ to match observations

Koyama & Ostriker (2009a)
\[ \sum_{SFR} = \epsilon_{ff}(n_{th}) \frac{\sum(n > n_{th})}{t_{ff}(n_{th})} \]

\(Q_{gas}\) = const, \(Q_\star\) = const
color (Bigiel et al 2008)

\[ \Sigma_{SFR} = \varepsilon_{ff}(n_{th}) \frac{\Sigma(n > n_{th})}{t_{ff}(n_{th})} \]

R series: \( Q_{gas} = \text{const}, \rho_* = \text{const} \)
SF predictions?

- $\Sigma_{\text{SFR}}$ in simulations is consistent with observations provided that the rate is based on self-gravitating gas mass.
- Simple SF recipes are often based on large-scale timescales, e.g.:
  - $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}/t_{\text{orb}}$
  - $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}/t_{\text{ff}} (Q_{\text{ave}} = \Sigma_{\text{gas}}/H)$
- These yield too-steep profiles.
- Need to resolve vertical disk structure, phase balance to obtain accurate SFR in simulations.
- Can $\Sigma_{\text{diffuse}}$ vs. $\Sigma_{\text{self-grav}}$ be predicted?

Koyama & Ostriker (2009a)
Observed $\Sigma_{H_2}/\Sigma_{HI}$

- Blitz & Rosolowsky (2006) found that
  
  \[ R_{mol} = \frac{\Sigma(H_2)}{\Sigma(HI)} \]

increase with galactic gas and stellar density as

\[ R_{mol} = \left( \frac{P_{ext}/k}{(3.5 \pm 0.6) \times 10^4} \right)^{0.92 \pm 0.07} \]

- BR $P_{ext}$ is estimate of midplane pressure
- Leroy et al. (2008) found similar relation, including for dwarfs if
  
  \[ \Sigma_{H_2} = t_{sf} \Sigma_{SFR} \]

\[ P_{ext} = 0.84(G\Sigma_*)^{0.5} \Sigma g \frac{v_g}{(h_*)^{0.5}}. \]
$R_{mol}$ in simulations

- vertically-resolved, multiphase, turbulent simulations have $R_{mol}$ similar to observations
- Hydrostatic models have $R_{mol}$ much larger than observed values ⇒ turbulence is important
- *What is the physical origin of the $R_{mol}$ -pressure relation?*

Koyama & Ostriker (2009b)
A new model for predicting $\Sigma_{\text{SFR}}$

• Formulation:
  – ISM has two components: gravitationally-bound clouds ($\Sigma_{\text{GBC}}$) and diffuse gas ($\Sigma_{\text{diff}}$)
  – Diffuse gas is in vertical dynamical equilibrium
    • Vertical gravity is from gas, stars, dark matter
  – In diffuse gas, midplane thermal pressure is consistent with two-phase thermal equilibrium
    • $P_{\text{th}} \approx (P_{\text{min,cold}} P_{\text{max,warm}})^{1/2} \equiv P_{\text{two-phase}}$
  – Two-phase pressure is set by local SFR:
    • $P_{\text{two-phase}} \propto \Sigma_{\text{SFR}} = \Sigma_{\text{gbc}} / t_{\text{sf}} = (\Sigma - \Sigma_{\text{diff}}) / t_{\text{sf}}$ for $t_{\text{sf}}$ constant
    • Assumes heating is dominated by photoelectric effect and $J_{\text{FUV}} \propto \Sigma_{\text{SFR}}$
Vertical Dynamical Equilibrium

- From momentum conservation, total midplane pressure of diffuse gas is

\[ P_{\text{tot}} \equiv \sigma_z^2 \rho_0 = \left( \langle v_{th}^2 \rangle + v_{\text{turb}}^2 + \Delta v_A^2 \right) \rho_0 = \int_{z_0}^{z_{\text{max}}} dz \rho g_z = \frac{\Sigma_{\text{diff}}}{2} \langle g_z \rangle \]

- Diffuse gas thermal pressure is \( P_{\text{th}} = P_{\text{tot}} / \alpha \)

\[ P_{\text{th}} = \langle v_{th}^2 \rangle \rho_0 = \frac{\langle v_{th}^2 \rangle}{\langle v_{th}^2 \rangle + v_{\text{turb}}^2 + \Delta v_A^2} P_{\text{tot}} \approx \frac{\Sigma_{\text{diff}}}{2 \alpha} \left[ \pi G (\Sigma_{\text{diff}} + 2 \Sigma_{\text{gbc}}) + 2 (2G \rho_*)^{1/2} \sigma_z \right] \]

- Consistent with results from numerical simulations (Koyama & Ostriker 2009b)

- GBC surface density is \( \Sigma_{\text{gbc}} = (\Sigma - \Sigma_{\text{diff}}) \)

- Surface density of star formation is \( \Sigma_{\text{SFR}} = \Sigma_{\text{gbc}} / t_{\text{sf}} \)
Two-phase pressure

• From numerical simulations with varying gravity, surface density (Piontek & Ostriker 2005, 2007), mean midplane
  \[ P_{th} \approx P_{\text{two-phase}} \equiv (P_{\text{min,cold}} P_{\text{max,warm}})^{1/2} \]

• In Solar neighborhood,
  \[ P_{th,0} \approx P_{\text{two-phase}} \approx 3000 \text{ K cm}^{-3} \]
  (Wolfire et al 2003)

• Dependence of \( P_{\text{two-phase}} \):
  \[
  \frac{P_{\text{two-phase}}}{k} = \left[ n_{\text{min}} T_{\text{min}} n_{\text{max}} T_{\text{min}} \right]^{1/2} \\
  = \Gamma \left[ \frac{T_{\text{min}} T_{\text{max}}}{\Lambda(T_{\text{min}}) \Lambda(T_{\text{max}})} \right]^{1/2}
  \]

• \( T_{\text{min}}, T_{\text{max}} \sim \text{const.} \); \( \Gamma \propto Z_d J_{\text{FUV}}, \Lambda \propto Z_g \Rightarrow \)
  \[ P_{\text{two-phase}} \propto J_{\text{FUV}} Z_d / Z_g \propto \Sigma_{\text{SFR}} \]

• \( P_{th} = P_{th,0} \frac{\Sigma_{\text{SFR}}}{\Sigma_{\text{SFR},0}} = P_{th,0} \frac{\Sigma_{\text{gbc}}}{(t_{sf} \Sigma_{\text{SFR},0})} \)
  closes system of equations
Results

• At high $\Sigma$, $\rho^*$: $\Sigma_{gbc} \gg \Sigma_{\text{diff}}$, $\Sigma_{\text{SFR}} = \Sigma / t_{sf}$

• At low $\Sigma$, $\rho^*$: $\Sigma_{\text{diff}} \gg \Sigma_{gbc}$

$$\Sigma_{\text{SFR}} \approx \frac{\Sigma_{\text{SFR},0}}{P_{\text{th},0}} \frac{\Sigma}{\alpha \left[ \frac{\pi G \Sigma}{2} + (2G\rho^*)^{1/2} \sigma_z \right]}$$

• Diffuse surface density in inner disk is limited:

$$\Sigma_{\text{diff}} < \frac{\alpha P_{\text{th},0}/(\pi G t_{sf} \Sigma_{\text{SFR},0})}{1 + g_{z,*} / g_{z,gbc}}$$
Results

• Self-gravitating-to-diffuse ratio:

\[
\frac{\Sigma_{gbc}}{\Sigma_{\text{diff}}} = \frac{\Sigma_{\text{SFR}} t_{sf}}{2P_{\text{tot}} \langle g \rangle_z} = \frac{P_{th} \left( \frac{\Sigma_{\text{SFR},0}}{P_{th,0}} \right) t_{sf}}{2P_{\text{tot}} \langle g \rangle_z} = \frac{\langle g \rangle_z \Sigma_{\text{SFR},0} t_{sf}}{2\alpha P_{th,0}}
\]

\[
\frac{\Sigma_{gbc}}{\Sigma_{\text{diff}}} \propto \langle g \rangle_z \propto \left[ \frac{\pi G \Sigma_{\text{diff}}}{2} + \pi G \Sigma_{gbc} + (2G\rho^*)^{1/2} \sigma_z \right]
\]

(similar to empirical $R_{mol} - P$ relation)
Comparison to empirical formulae -- NGC 5055

---

(a) $\Sigma_{\text{SFR}}$ vs. $\Sigma$ [M$_\odot$ kpc$^{-2}$ yr$^{-1}$]

(b) $\Sigma_{\text{SFR}}/\Sigma$ vs. $\Sigma$ [M$_\odot$ kpc$^{-2}$]

(c) $\Sigma_{\text{SFR}}, \Sigma, \Sigma_{\text{HI}}, \Sigma_{\text{dust}}$ vs. $R$ [kpc]

(d) $\Sigma_{\text{SFR}}$ vs. $R$ [kpc]

4/28/10
Outer and inner disks

- $P_{th} = P_{two-phase} \Rightarrow \Sigma_{diff} g_z = \text{const} \times \Sigma_{SFR} \Rightarrow$
  $$\Sigma_{diff} \left( \pi G \Sigma_{gbc} + (2 \ G \ \rho_*)^{1/2} \sigma_z \right) \sim \text{const} \times \Sigma_{gbc}$$
  
- Where $\Sigma_{gbc}$ is low, $\Sigma_{SFR} \propto \Sigma_{gbc} \propto \Sigma_{diff} \rho_*^{1/2}$
  
i.e. SFR increases until heating is sufficient to balance cooling at midplane pressure

- Where $\Sigma_{gbc}$ is high, $\Sigma_{diff}$ is limited due to increase of cooling with gravitational compression
  
  - heating/mass $\propto J_{FUV} \propto \Sigma_{gbc}$
  
  - cooling/mass $\propto n \sim \Sigma_{diff} / H \sim g_z \Sigma_{diff} / \sigma_z^2$
    $$\propto \Sigma_{gbc} \left( 1 + g_* / g_{gbc} \right) \Sigma_{diff}$$
  
i.e. $\Sigma_{diff}$ decreases (mass “dropout”) until cooling matches heating
Approach to SF Equilibrium

• If diffuse fraction $\Sigma_{\text{diff}}/\Sigma$ is high...

• From vertical dynamics, midplane $P_{th} \sim \Sigma_{\text{diff}} (2G\rho_*)^{1/2} \langle v_{\text{th}} \rangle / \alpha^{1/2}$ is high

• $\Sigma_{\text{gbc}} = \Sigma - \Sigma_{\text{diff}}$ is low $\Rightarrow \Sigma_{\text{SFR}}$ low

• $P_{\text{two-phase}}/k \sim 10^6 \text{K cm}^{-3} \frac{\Sigma_{\text{SFR}}}{M_{\odot} \text{ kpc}^{-2} \text{yr}^{-1}}$ is low

• Warm medium condenses to make cold clouds

• Cold clouds collect into GBCs; lowers $\Sigma_{\text{diff}}$ and $P_{th}$

• Increase in $\Sigma_{\text{GBC}}$ raises $\Sigma_{\text{SFR}}$

• Higher $\Sigma_{\text{SFR}}$ raises $P_{\text{two-phase}}$
Approach to SF Equilibrium

• If diffuse fraction $\Sigma_{\text{diff}} / \Sigma$ is low…

• From vertical dynamics, midplane $P_{th} \sim \Sigma_{\text{diff}} (2G\rho_*)^{1/2} \langle v_{th} \rangle / \alpha^{1/2}$ is low

• $\Sigma_{\text{gbc}} = \Sigma - \Sigma_{\text{diff}}$ is high $\Rightarrow \Sigma_{\text{SFR}}$ high

• GBCs and cold clouds evaporate to make warm medium

• Increase in $\Sigma_{\text{diff}}$ raises midplane $P_{th}$

• Decrease in $\Sigma_{\text{GBC}}$ lowers $\Sigma_{\text{SFR}}$

• Lower $\Sigma_{\text{SFR}}$ reduces $P_{\text{two-phase}}$
Summary

• Relative abundance of self-gravitating vs. diffuse gas determines the SFR
• In dynamical equilibrium $P_{\text{diff}} \sim \Sigma_{\text{diff}} g_z$
• In thermal equilibrium, $P_{\text{two-phase}} \propto J_{\text{FUV}} \propto \Sigma_{\text{SFR}}$
• If $P_{\text{diff}} \approx P_{\text{two-phase}}$, $\Sigma_{\text{SFR}} \propto \Sigma_{\text{diff}} g_z$
  $g_z \sim (G\rho_*)^{1/2}\sigma_z$ in outer disks $\Rightarrow \Sigma_{\text{SFR}} \propto \Sigma(\rho_*)^{1/2}$
  i.e. SFR is just enough so that heating balances cooling at imposed pressure
• Strong cooling at high pressure limits the carrying capacity of diffuse gas in inner disks
• Results for $\Sigma_{\text{SFR}}$ as a function of $R$, $\Sigma$, $\Sigma_*$ agree with observations, esp. for flocculent galaxies