Feedback Regulated SFRs and HI 21cm Lines

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(Naive) Dimensional Analysis

- SFR = gas contents/dynamical time
ATOMIC GAS DOMINATED

STARBURST

MOL. GAS DOMINATED
(Naive) Dimensional Analysis

- SFR = gas contents/dynamical time
- $t_{\text{dyn}} \sim 1/(G\rho)^{1/2} \sim 50\text{Myr}$ for $\rho = 0.1\text{M}_{\odot}/\text{pc}^3$
- $t_{\text{dep}} = \frac{\Sigma_{\text{SFR}}}{\Sigma} \sim 2\text{Gyr}$ (e.g., Bigiel et al. 2008)
(Naive) Dimensional Analysis

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- \( t_{\text{dyn}} \sim 1/(G\rho)^{1/2} \sim 50\text{Myr} \) for \( \rho = 0.1\text{M}_\odot/\text{pc}^3 \)
- \( t_{\text{dep}} = \Sigma_{\text{SFR}}/\Sigma \sim 2\text{Gyr} \) (e.g., Bigiel et al. 2008)
- \( \epsilon_{\text{ff}} \sim 1-2\% \) (e.g., Krumholz & Tan 2007; Krumholz et al. 2011)
- inefficient star formation
Theory

Ostriker et al. (2010); Ostriker & Shetty (2011);
CGK, Kim, Ostriker (2011)
EQUILIBRIUM MODEL

Gravity
weight
Dark Matter
Star
Gas

≈

Pressure Force
Pressure Difference

Thermal
Turbulent
Magnetic
Cosmic Ray
Radiation
...

Ostriker, McKee, Leroy (2010); CGK, Kim, Ostriker (2011)
Equilibrium Model

Gravity weight

Dark Matter Star Gas

Pressure Force
Midplane Pressure

Thermal

Cooling ≈ Heating

Turbulent

Dissipation ≈ Driving

Ostriker, McKee, Leroy (2010); CGK, Kim, Ostriker (2011)
Regulation by Feedback

Gravity

Dark Matter

Star

Gas

Pressure Force

Midplane Pressure

Thermal

Cooling < Heating

Turbulent

Dissipation < Driving

Over-Production of Stars

Ostriker, McKee, Leroy (2010); CGK, Kim, Ostriker (2011)
REGULATION BY FEEDBACK

Gravity
Weight

Dark Matter
Star
Gas

Under-Production of Stars

Pressure Force
Midplane Pressure

Thermal
Cooling > Heating

Turbulent
Dissipation > Driving

Ostriker, McKee, Leroy (2010); CGK, Kim, Ostriker (2011)
REGULATION BY FEEDBACK

Gravity:
- Weight
- Dark Matter
- Star
- Gas

Equilibrium SFR:
- Pressure Force
  - Midplane Pressure

Thermal:
- Cooling ≈ Heating

Turbulent:
- Dissipation ≈ Driving

Ostriker, McKee, Leroy (2010); CGK, Kim, Ostriker (2011)
Simulations

CGK, Kim, Ostriker (2011); CGK, Ostriker, Kim (2013)
Goal of Numerical Simulations

Gravity Weight

\[ \pi G \Sigma^2/2 + \Sigma (2G \rho^*)^{1/2} \sigma \]

Pressure Force

Midplane Pressure

Radiative Feedback

\[ n \Lambda(T) \]

\[ \Gamma \propto \Sigma_{sfr} \]

SN Feedback

\[ \Sigma v^2/H \]

\[ (\rho/\text{m}^*) \Sigma_{sfr} \]
**SF feedback prescriptions**

- **Mechanical Feedback by SN**
  - SN event occurs in dense clouds where unresolved gravitational collapse occurs: \( \rho > \rho_{\text{crit}} \) WHERE \( \rho_{\text{crit}} \) IS DETERMINED TO BE \( \Lambda_j \approx 2\Delta \)

- **Total momentum per SN** is \( p_* = 3 \times 10^5 M_\odot \text{km/s} \) (Cioffi et al. 1988; CGK & Ostriker 2014)

- **Radiative Feedback**
  - \( \Gamma \propto J_{\text{FUV}} \propto \Sigma_{\text{SFR}} \)
**TIME EVOLUTIONS**

Surface Density in XY  
Mean Density in XZ
SFRs (and other physical properties) are well saturated after 1 or 2 vertical oscillations (~0.3-0.6 $t_{\text{orb}}$).
SFR vs Gas Contents/Time

GAS FREE-FALL TIME

\[ \epsilon_{ff} \sim 0.6\% \]

GAS FREE-FALL TIME

\[ \epsilon_{ver} \sim 0.2\% \]
Turbulent Velocity

- $\sim 6$ km/s, irrespective of SFR
- $\sigma = \varepsilon_{\text{dyn}} \left( \frac{p_*/m_*}{m_*} \right) \sim 6$ km/s for $\varepsilon_{\text{ver}} \sim 0.2\%$
THERMAL ENERGY BALANCE

MIDPLANE THERMAL PRESSURE IS NEARLY LINEARLY PROPORTIONAL TO THE SFR SURFACE DENSITY

\[ P_{\text{th}} \propto P_{\text{two}}^{0.85} \]

\[ P_{\text{two}} / k_B = 3,110 \text{ K cm}^{-3} f_{\text{rad}} \left( \frac{\Sigma \text{SFR}}{\Sigma \text{SFR}_0} \right) \]
Turbulent Energy Balance

Midplane turbulent pressure is nearly linearly proportional to the SFR surface density.

\[ P_{\text{turb}} \propto P_{\text{driv}}^{0.9} \]

\[ P_{\text{driv}}/k_B = 8,990 \text{ K cm}^{-3} \left( \frac{\Sigma \text{SFR}}{\Sigma \text{SFR},0} \right) \]
VERTICAL DYNAMICAL EQUILIBRIUM

ON AVERAGE SENSE, TOTAL PRESSURE CAN BE VERY WELL ESTIMATED BY VERTICAL DYNAMICAL EQUILIBRIUM (REL. DIFF. IS LESS THAN 12%)

$$P_{th} + P_{turb} \approx \Sigma(\sqrt{2G\rho_\star \sigma_z} + \pi G\Sigma/2)$$
**Numerical Simulations**

**Gravity Weight**

\[ \pi G \Sigma^2/2 + \Sigma (2G \rho^*)^{1/2} \sigma \]

**Pressure Force**

**Midplane Pressure**

- **Radiative Feedback**
  \[ n \Lambda(T) = \Gamma \alpha \Sigma_{sfr} \]

- **SN Feedback**
  \[ \Sigma v^2/H = (p^*/m^*) \Sigma_{sfr} \]
\[ P_{\text{tot}} \sim P_{\text{th}} + P_{\text{turb}} \sim P_{\text{two}} + P_{\text{driv}} \propto \Sigma_{\text{SFR}} \]
HI Synthetic Observations

CGK, Ostriker, Kim (2014)
\( x = -s \cos b \cos l \)
\( y = -s \cos b \sin l \)
\( z = s \sin b \).

\( 10^4 \) sightlines uniformly in \( dl \) and \( ds \sin(b) \).
\[ T_s = \frac{T_R + y_c T_k + y_\alpha T_\alpha}{1 + y_c + y_\alpha}, \]

\[ \phi(v_{ch}) = \frac{1}{\sqrt{\pi} \Delta v} \frac{c}{v_0} e^{-[(v_{ch} - v)/\Delta v]^2}, \]
LOS Data

\[ T_s = \frac{T_R + y_c T_k + y_\alpha T_\alpha}{1 + y_c + y_\alpha}, \]

Channel Data

Emissivity \( (j) \)

Abs. coeff. \( (\kappa) \)

Synthetic Spectra

\[ \phi(v_{ch}) = \frac{1}{\sqrt{\pi} \Delta v} \frac{c}{v_0} e^{-[(v_{ch}-v)/\Delta v]^2}, \]
SIMULATION

SYNTHETIC OBSERVATION

OBSERVATION

LAB SURVEY: Kalberla et al. (2005)
BRIGHTNESS T VS OPTICAL DEPTH

- OVERALL AGREEMENT BETWEEN MOCK AND REAL OBSERVATIONS
- PRESENCE OF UNSTABLE GAS
Spin Temperature vs Mass Fractions

- **GOOD Probe to CNM Mass Fraction**
  - $T_{\text{cold}}$ should be assumed
- **Moderate Discriminator between WNM and UNM**

Mean Spin Temperature
**Spin Temperature vs Mass Fractions**

- **GOOD Probe to CNM Mass Fraction**
  - $T_{\text{cold}}$ should be assumed
- **Moderate Discriminator between WNM and UNM**

*Stanimirovic et al. (2014)*
SUMMARY

• (INTERNAL) regulation of SFR is well described by the equilibrium model: $\Sigma_{SFR} \propto P_{tot}$

• SIMPLE MECHANICAL FEEDBACK FROM SN reproduces dynamical saturation states and HI properties of galactic disks

• FURTHER DETAILS WILL BE INVESTIGATED FROM THE MODELS WITH MORE REALISTIC FEEDBACK: TIME DELAY, HII REGION, THERMAL SN FEEDBACK