The connection between local and global star formation in galaxies

Vadim Semenov
University of Chicago, PhD -> Harvard-Smithsonian CfA, Hubble fellow

with Andrey Kravtsov (UChicago) and Nick Gnedin (Fermilab)
The value of gas depletion time is a long-standing puzzle

\[ \tau_{\text{dep}} = \frac{M_{\text{gas}}}{\dot{M}_*} \sim 2-10 \text{ Gyr} \]

\( \tau_{\text{dep}} \) is much longer than any dynamical timescale relevant for SF:

- \( t_{\text{turb}} = \frac{h}{\sigma} \sim 10 - 30 \text{ Myr} \)
- \( t_{\text{ff}} = \sqrt{\frac{3\pi}{32G\rho}} \sim 2 - 20 \text{ Myr} \)
- \( t_{\text{orb}} = \frac{2\pi R}{V_{\text{rot}}} \approx 200 \text{ Myr at } R_{\odot} \)

i.e. star formation in galaxies is surprisingly inefficient.

Inefficiency of actively star-forming regions is an important factor:

\[ \tau_{\text{dep,sf}} = \frac{M_{\text{sf}}}{\dot{M}_*} = \frac{t_{\text{ff}}}{\epsilon_{\text{ff}}} \sim 0.1 - 0.5 \text{ Gyrs} \]

but their depletion times are too short to explain global \( \tau_{\text{dep}} \)
Isolated \( \sim L^* \) galaxy simulation

- 451 Myr
- 5 kpc

- Young stars (age < 20 Myr)
- Gas density (cm\(^{-3}\))
- Temperature (K)
- Subgrid turbulent velocity (km/s)

[Graphs and colors representing various parameters]
Gas evolution between star-forming and non-star-forming states

Star formation criterion: \( \alpha_{\text{vir}} < 10 \)

\[
\alpha_{\text{vir}} = \frac{2E_{\text{kin}}}{E_{\text{grav}}} \propto \frac{\sigma^2}{\rho}
\]

Local star formation rate:

\[
\dot{\rho}_* = \epsilon_{\text{ff}} \frac{\rho}{t_{\text{ff}}} \quad \epsilon_{\text{ff}} = 1\%
\]

Krumholz & McKee '05; Padoan & Nordlund '11; Padoan+12\textsuperscript{,17}; Federrath & Klessen '12; Burkhart '18

Gas evolution between star-forming and non-star-forming states

- Gas cycles between SF and non-SF states on <100 Myr timescale
- Feedback disperses SF regions making SF stages short
- Most of the time gas spends in the non-SF state

Physical origin of long gas depletion times

Gas depletion time:

\[
\tau_{\text{dep}} = \frac{M_g}{\dot{M}_*} = \frac{1}{f_{\text{sf}}} \frac{M_{\text{sf}}}{\dot{M}_*} = \frac{\tau_{\text{dep},\text{sf}}}{f_{\text{sf}}}
\]

Depletion time of star-forming gas explicitly depends on the SF recipe

\[
\tau_{\text{dep},\text{sf}} = \frac{\rho}{\dot{\rho}_*}
\]

Mass fraction of star-forming gas:

\[
f_{\text{sf}} = \frac{M_{\text{sf}}}{M_g} \sim \frac{t_{\text{sf}}}{t_{\text{sf}} + t_{\text{nsf}}} = \left(1 + \frac{t_{\text{nsf}}}{t_{\text{sf}}} \right)^{-1}
\]

(Depletion time) = (Depletion time in SF state) + (Total time in non-SF state over \(N_{\text{dep}}\) cycles)

Although each cycle is short, depletion is long because the number of cycles is large

Semenov, Kravtsov, Gnedin 2018 ApJ 861, 4
Direct analogy: “inefficiency” of football

Field-crossing time ~ 20 seconds

UEFA Champions League 2018–19
Average # of goals scored per match: 2.93
Dependence of depletion time on local SF efficiency

Points – simulation results
Lines – model predictions

Global depletion time (Gyr)

Local SF efficiency \( \epsilon_{\text{ff}} \) (%)

By definition:

\[
\tau_{\text{dep, sf}} = \frac{\rho}{\dot{\rho}_*} \propto \epsilon_{\text{ff}}^{-1}
\]

Feedback limits SF stages:

\[
t_{\text{sf}} \propto \epsilon_{\text{ff}}^{-1}
\]

Model explains self-regulation!
(i.e., insensitivity of global depletion time to local \( \epsilon_{\text{ff}} \))

Dobbs+’11; Agertz+’13,’15; Hopkins+’13

Semenov, Kravtsov, Gnedin 2018 ApJ 861, 4

\[
\dot{\rho}_* = \epsilon_{\text{ff}} \frac{\rho}{t_{\text{ff}}}
\]

SFR (M\(_{\odot}\)/yr)

Lookback time (Myr)
Dependence of depletion time on local SF efficiency

By definition:

$$\tau_{\text{dep}, \text{sf}} = \frac{\rho}{\dot{\rho}_*} \propto \epsilon_{\text{ff}}^{-1}$$

Feedback limits SF stages:

$$t_{\text{sf}} \propto \epsilon_{\text{ff}}^{-1}$$

Model explains self-regulation!

(i.e., insensitivity of global depletion time to local $\epsilon_{\text{ff}}$)

Dobbs+'11; Agertz+'13,'15; Hopkins+'13,'18

Star-forming gas mass fraction has opposite behavior:

$$f_{\text{sf}} \sim \left(1 + \frac{t_{\text{nsf}}}{t_{\text{sf}}}\right)^{-1}$$

$f_{\text{sf}}$ can be used to constrain $\epsilon_{\text{ff}}$

Hopkins+'13

Semenov, Kravtsov, Gnedin 2018 ApJ 861, 4
Summary

A simple framework based on the physical picture of ISM gas cycling explains the origin of gas depletion times in galaxies

\[ \tau_{\text{dep}} \sim \frac{\tau_{\text{dep,sf}}}{t_{\text{sf}}} \]

Global \( \tau_{\text{dep}} \) is longer than \( \tau_{\text{dep,sf}} \) in SF regions because a large fraction of the time gas spends in the non-SF state.

\( \tau_{\text{dep}} \) is much longer than dynamical timescales (\( t_{\text{nsf}} \)) because gas has to go through a large number of cycles.

\( \tau_{\text{dep}} \) shows two limiting regimes with qualitatively different dependence on star formation and feedback parameters.

Other insights from the model:

- The origin of constant depletion time of molecular gas on kiloparsec and larger scales (linear molecular Kennicutt-Schmidt relation)
- Insights into the scatter of depletion times (scatter of the Kennicutt-Schmidt relation)
- Evolution of depletion times in galaxies