The physical origin of long gas depletion times in galaxies

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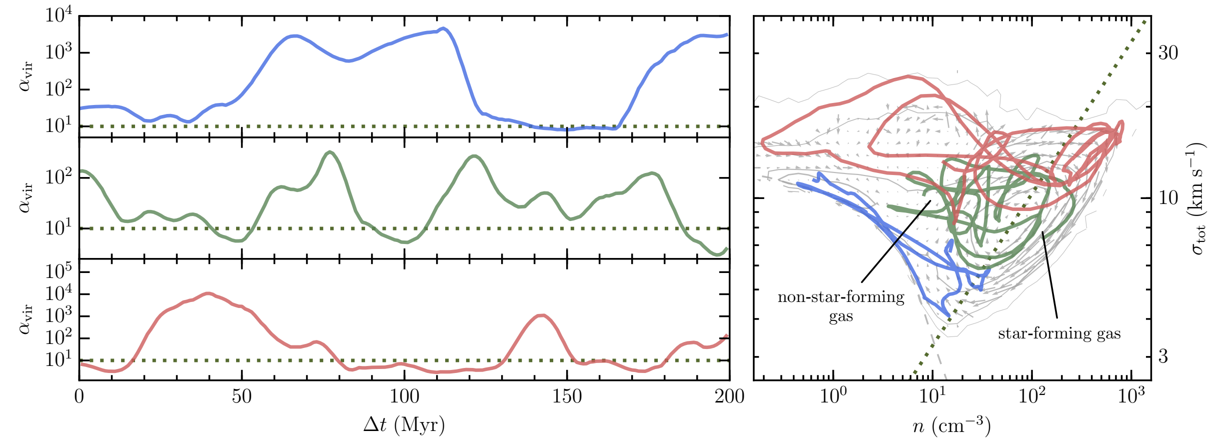

Evolution of three illustrative gas tracers in a simulated galaxy. Left panels: the evolution of $\alpha_{\rm vir}$; right panel: tracers trajectories in the plane of gas number density, n, and total velocity dispersion, $\sigma_{\rm tot} = \sqrt{\sigma_{\rm t}^2 + c_{\rm s}^2}$, which includes both turbulent and thermal velocities. The gray contours and arrows indicate the distribution of gas tracers and their net fluxes. The thick dotted lines correspond to the adopted star formation threshold, $\alpha_{\rm vir} = 10$. The figure is copied from the original paper.

Galaxies form stars inefficiently. Indeed, the typical time scale on which star-forming galaxies deplete their gas ($\tau_{\rm dep} \equiv M_{\rm g}/\dot{M}_\star \sim 2-10$ Gyrs for total gas and $\tau_{\rm dep,H_2} \equiv M_{\rm H_2}/\dot{M}_\star \sim 1-3$ Gyrs for molecular gas) is substantially longer than any dynamical time scales in the interstellar medium (ISM): e.g., turbulent turnover time is $t_{\rm turb} = h_{\rm disk}/\sigma_{\rm turb} \sim 10-30$ Myr, free-fall time at the average ISM density is $t_{\rm ff,0} \equiv \sqrt{3\pi/32G\rho_0} \sim 10-50$ Myr. Such long $\tau_{\rm dep}$ cannot be explained by inefficiency of local star formation alone because local depletion times in dense star-forming regions are also relatively short: $\tau_\star \equiv M_{\rm sf}/\dot{M}_\star \lesssim 500$ Myr.

Using the insights from a galaxy simulation that reproduces observed depletion time, we formulate a simple physical model that explains why $\tau_{\rm dep}$ is long. In this model, ISM gas frequently cycles between star-forming and non-star-forming states, converting only a small fraction of its mass into stars on each cycle. This fraction is small because of both inefficient star formation in the star-forming state and efficient feedback and dynamical processes that rapidly destroy star-forming regions. Thus, before global depletion, gas transits between star-forming and non-star-forming states multiple times, which results in a long $\tau_{\rm dep}$.

The figure illustrates the cycling of ISM gas in our simulation. In this simulation, gas becomes star-forming when its virial parameter,

$$\alpha_{\rm vir} \equiv \frac{5\sigma_{\rm 1D}^2 R}{GM} \approx 9.35 \frac{(\sigma_{\rm tot}/10~{\rm km~s^{-1}})^2}{(n/100~{\rm cm^{-3}})(\Delta/40~{\rm pc})^2},$$

becomes $\alpha_{\rm vir} < 10$, typical for observed star-forming regions of a size comparable to our resolution, $\Delta = 40$ pc. In such gas, local depletion time is parametrized with the star formation efficiency per free-fall time, $\tau_\star = \tau_{\rm ff}/\epsilon_{\rm ff}$, assuming $\epsilon_{\rm ff} = 1\%$.

We find that on each cycle gas spends on average $t_{\rm nsf} \sim 10-100$ Myr in non-star-forming and $t_{\rm sf} \sim 5-15$ Myr in star-forming state (see also left panels in the figure). Given $\tau_\star \sim 500$ Myr obtained in our simulation, such short $t_{\rm sf}$ imply that on average $N_{\rm c} = \tau_\star/t_{\rm sf} \sim 30-100$ cycles are required for global depletion, which results in Gyrs-long $\tau_{\rm dep}$:

$$\tau_{\rm dep} = N_{\rm c}(t_{\rm nsf} + t_{\rm sf}) = N_{\rm c} t_{\rm nsf} + \tau_\star.$$

Our model can be used to interpret trends of depletion times with the properties of observed galaxies and the parameters of star formation and feedback recipes in simulations. For example, the above expression explains how feedback self-regulates star formation rate in simulations and makes it insensitive to the local $\epsilon_{\rm ff}$. Specifically, efficient feedback ties the duration of star-forming stages to local depletion times making $N_{\rm c}$ independent of $\tau_\star$ and $\epsilon_{\rm ff}$ and thus $\tau_{\rm dep}$ becomes insensitive to $\epsilon_{\rm ff}$ when the first term in the above expression dominates.