From Interstellar Clouds to Star-Forming Galaxies: Universal Processes?
Proceedings IAU Symposium No. 315, 2015
P. Jablonka, Ph. André & F. van der Tak, eds.

doi:10.1017/S1743921316007225

Feedback Regulated Turbulence, Magnetic Fields, and Star Formation Rates in Galactic Disks

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Abstract. We use three-dimensional magnetohydrodynamic (MHD) simulations to investigate the quasi-equilibrium states of galactic disks regulated by star formation feedback. We incorporate effects from massive-star feedback via time-varying heating rates and supernova (SN) explosions. We find that the disks in our simulations rapidly approach a quasi-steady state that satisfies vertical dynamical equilibrium. The star formation rate (SFR) surface density self-adjusts to provide the total momentum flux (pressure) in the vertical direction that matches the weight of the gas. We quantify feedback efficiency by measuring feedback yields, $\eta_c \equiv P_c/\Sigma_{\rm SFR}$ (in suitable units), for each pressure component. The turbulent and thermal feedback yields are the same for HD and MHD simulations, $\eta_{\rm th} \sim 1$ and $\eta_{\rm turb} \sim 4$, consistent with the theoretical expectations. In MHD simulations, turbulent magnetic fields are rapidly generated by turbulence, and saturate at a level corresponding to $\eta_{\rm mag,t} \sim 1$. The presence of magnetic fields enhances the total feedback yield and therefore reduces the SFR, since the same vertical support can be supplied at a smaller SFR. We suggest further numerical calibrations and observational tests in terms of the feedback yields.

Keywords. galaxies: ISM, galaxies: star formation, galaxies: magnetic fields, turbulence, MHD, methods: numerical

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1. Introduction

"What determines the SFR in galaxies?" In order to answer this long-standing, fundamental question, a correlation between the SFR and the gas content has been extensively explored. Among many studies since the pioneering work by Schmidt (1959), Kennicutt (1998) presents a well-defined power-law relationship between total gas surface density (Σ) and the SFR surface density ($\Sigma_{\rm SFR}$) for galaxies as a whole, $\Sigma_{\rm SFR} \propto \Sigma^{1+p}$ with $p = 0.4$. This observed correlation was soon widely accepted as the "Kennicutt-Schmidt law" (KS law) and used as a star formation recipe for large scale galaxy formation and cosmological simulations.

The observed power-law index with $p = 0.4$ of the KS law makes it tempting to infer a simple dimensional relationship, $\Sigma_{\rm SFR} = \Sigma/t_{\rm dep}$, with the gas depletion time related to the gas free-fall time, $t_{\rm dep} \propto t_{\rm ff} \sim (G\rho)^{-1/2}$. With a fixed gas scale height, this relation would imply $p = 0.5$, close to the observed value. Many theoretical studies based on this simple argument have been investigated, with low star formation efficiency per free-fall time $\epsilon_{\rm ff} \equiv t_{\rm ff}/t_{\rm dep} \sim 1\%$ (e.g., Krumholz *et al.* 2012). On scales of molecular clouds, the low efficiency has been attributed to the broad density probability distribution function generated by supersonic turbulence (e.g., Padoan *et al.* 2014 and references therein), but it is unclear whether this picture can be simply extended to large scales (>0.1-1 kpc).

Moreover, recent high-resolution observations of nearby galaxies reveal more complex correlations (Bigiel *et al.* 2008; Leroy *et al.* 2008). In particular, the simple power-law relation between $\Sigma_{\rm SFR}$ and Σ fails in the low surface density regime ($\Sigma < 10\ M_\odot\ {\rm pc}^{-2}$), where the gas is predominantly atomic. Rather, the power-law index becomes steeper and/or varies from one galaxy to another. The SFR shows a tighter correlation with the stellar surface density Σ_* or its combination with Σ (e.g., Leroy *et al.* 2008).

The increasing complexity of the observed KS law in the low-Σ regime implies that Σ is not the only control parameter of star formation. In this article, we describe a fundamental correlation based on physical causality between the SFR surface density and the total pressure ($P_{\rm tot}$). In § 2 and § 3, we respectively summarise the theory from Ostriker *et al.* (2010); Ostriker & Shetty (2011); Kim *et al.* (2011) and simulations from Kim *et al.* (2011, 2013); Kim & Ostriker (2015).

2. Theory

The interstellar medium (ISM) disk in an equilibrium state should satisfy vertical force balance between gravity and pressure gradients, which can be directly derived from the momentum equation of MHD.† In the integrated form, the vertical dynamical equilibrium can be written as $\mathcal{W} = \Delta P_{\rm tot}$, a balance between the total weight of gas and the momentum flux differences across the gas disk.

The other condition to satisfy is the energy/momentum equilibrium between gain from star formation feedback and loss in the dissipative ISM. Since cooling and turbulence dissipation time scales are typically short compared to dynamical time scales, continuous injection of energy and momentum is necessary to heat gas and drive turbulence. The far-UV radiation from massive young stars is the major heating source in the atomic ISM via the photoelectric effect onto grains. The momentum injection from SNe is the dominant source of the turbulence driving. Because the energy and momentum from stellar radiation and SNe fundamentally derive from nuclear processes, SF feedback is a highly efficient way to balance losses in the ISM.

Figure 1 shows a schematic diagram for (a) energy/momentum equilibrium and (b) vertical dynamical equilibrium as well as the connection between two equilibria. Since the ISM mostly gains energy/momentum through star formation feedback, the total pressure (momentum flux) is set by the SFR surface density. The total pressure determined by Figure 1(a) provides the vertical support in Figure 1(b), which should match with the dynamical equilibrium pressure $P_{\rm DE}$ (or the weight of the gas $\mathcal{W}$).

The equilibrium is naturally a stable one. For example, if the SFR gets higher than equilibrium, enhanced thermal heating and turbulence driving set the total pressure higher than the equilibrium level. The disk becomes thermally and dynamically hotter, vertically expanding and dispersing cold, dense clumps to quench further star formation. On the other hand, when the SFR drops below of the level of equilibrium, reduced feedback makes the disk thermally and dynamically cold and susceptible to gravitational collapse, forming more stars. Therefore, the SFR is self-regulated to satisfy both equilibria shown in Figure 1.

† Although the resulting equation would be essentially the same with so called *hydrostatic equilibrium* with an effective (total) sound speed, we prefer to term this *vertical dynamical equilibrium* since the ISM is highly dynamic and equilibrium holds only in an average sense.

https://doi.org/10.1017/S1743921316007225 Published online by Cambridge University Press

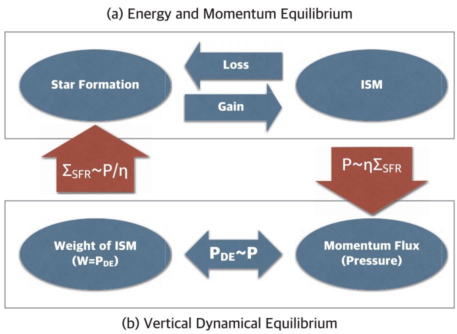

Figure 1. Schematic diagram of the equilibrium theory. (a) Energy/momentum equilibrium sets the total pressure in response to the SFR, $P_{\rm tot} \sim \eta\Sigma_{\rm SFR}$. (b) Vertical dynamical equilibrium constrains the total momentum flux (pressure), $P_{\rm tot} \sim P_{\rm DE}$, and hence the SFR, $\Sigma_{\rm SFR} \sim P_{\rm DE}/\eta$.

In order to quantify this process, we define the *feedback yield* of any pressure component "c" (= thermal, turbulent, or magnetic) in suitable units as

$$\eta_c \equiv \frac{P_{c,3}}{\Sigma_{\rm SFR,-3}}, \qquad (2.1)$$

where $P_{c,3} \equiv P_c/(10^3 k_B \text{ cm}^{-3} \text{ K})$ and $\Sigma_{\rm SFR,-3} \equiv \Sigma_{\rm SFR}/(10^{-3}\ M_\odot \text{ pc}^{-2} \text{ Myr}^{-1})$. The feedback yield can be considered as a energy/momentum conversion efficiency of the star formation feedback, depending on the detailed thermal and dynamical processes in the ISM. To first order, we can simply connect the thermal and turbulent pressures with the SFR surface density linearly. Our adopted cooling and heating formalism gives $\eta_{\rm th} = 1.2$, and the momentum feedback prescription with specific momentum injection per star formation $(p_*/m_*) = 3000$ km/s gives $\eta_{\rm turb} = 3.6$.

3. Numerical Simulations

Utilizing the *Athena* code (Stone *et al.* 2008), we run three-dimensional simulations for the local patch of galactic disks including optically thin cooling, galactic differential rotation, self-gravity, vertical external gravity, and magnetic fields. We apply a spatially-constant, time-varying heating rate $\Gamma \propto \Sigma_{\rm SFR}$, and also momentum injection from SNe $\propto \Sigma_{\rm SFR}$. While in some other recent simulations, the SFR and SN rate is pre-specified and constant in time, for all of our models the time-dependent SFR and SN rate are self-consistently set by self-gravitating localized collapse.

Our simulations achieve a quasi-steady state after a few vertical oscillation times (less than one orbit time). We confirm vertical dynamical equilibrium using horizontally and temporally averaged vertical profiles that are converged for different initial and boundary conditions as well as numerical resolutions. For a wide range of disk conditions such that $0.1 < \Sigma_{\rm SFR,-3} < 10$, the equilibrium thermal and turbulent pressures give consistent feedback yields, $\eta_{\rm th} = 1.3\Sigma_{\rm SFR,-3}^{0.14}$ and $\eta_{\rm turb} = 4.3\Sigma_{\rm SFR,-3}^{0.11}$, respectively.

In MHD simulations, the time scales to reach a quasi-steady state depend on the initial magnetizations. For initial magnetic energy varying by two orders of magnitude, however, saturated states converge to the same asymptote for the turbulent magnetic fields, whose energy is about a half of the turbulent kinetic energy. The final turbulent magnetic fields provide additional vertical support that is directly related to the turbulent pressure and hence the SFR, giving rise to $\eta_{\rm mag,t} \sim 1$ for solar neighborhood models. Since we fix disk parameters for MHD models, further investigation is necessary to calibrate the detailed dependence of $\eta_{\rm mag,t}$ on $\Sigma_{\rm SFR}$.

4. Concluding Remarks

We have developed a theory for self-regulation of the SFR based on energy/momentum equilibrium and vertical dynamical equilibrium, and confirmed and calibrated this theory with numerical simulations. The former equilibrium gives rise to the correlation between $\Sigma_{\rm SFR}$ and $P_{\rm tot}$ owing to the physical causality; the higher/lower SFR causes higher/lower energy density and momentum flux ($P_{\rm tot} = \eta\Sigma_{\rm SFR}$). The latter equilibrium sets $\Sigma_{\rm SFR}$ based on the requirement $P_{\rm tot} = P_{\rm DE}$. Therefore, correlations between $\Sigma_{\rm SFR}$ and galactic properties are caused by dependences embedded in $P_{\rm DE}$ such that

$$P_{\rm DE} \equiv \mathcal{W} \approx \frac{\pi G\Sigma^2}{2} + \Sigma\sigma_z(2G\rho_{\rm sd})^{1/2} \qquad (4.1)$$

where $\rho_{\rm sd}$ is the midplane density of stars plus dark matter and σ_z is total vertical velocity dispersion. The observed complexities in the KS law for the low-Σ regime naturally arise when the second term in RHS of Equation (4.1) dominates.

Lastly, we suggest further numerical calibrations and observational tests of the equilibrium theory. Theorists who include any form of star formation feedback can calibrate η_c from a "P_c-$\Sigma_{\rm SFR}$" plot for each measured pressure (turbulent, thermal, magnetic) in their simulations. It could be interesting to check consistency and/or to investigate differences among simulations with different setups, including comparing global *vs.* local models. Additional calibrations of other components such as radiation pressure and cosmic ray pressure would enable comparison of the relative importance of each component.

It is difficult to measure the total pressure directly from observations even in the solar neighborhood. However, the dynamical equilibrium pressure can be determined from direct observables (such as those from Leroy *et al.* 2008) with proper assumptions.† From the "$P_{\rm DE}$-$\Sigma_{\rm SFR}$" observed plot, one can measure total feedback yield $\eta = P_{\rm DE,3}/\Sigma_{\rm SFR,-3}$. This can be compared with the sum of the theoretical values η_c as a test of the self-regulation theory, also constraining the dominant sources of SF feedback.

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† Please refer to the following link for a practical guide: `http://www.astro.princeton.edu/~cgkim/to_observers.html`

https://doi.org/10.1017/S1743921316007225 Published online by Cambridge University Press