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Evolution of the Gas Density in a Simulated Star-forming Cloud with Stellar Feedback

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Abstract

Star formation involves gravity, turbulence, magnetic fields, and feedback from new stars through jets, radiation and winds. The evolution of the density probability distribution function (ρ-PDF) is directly related to the star formation rate (SFR), forming the basis of several star formation models. We utilize two runs from the STARFORGE simulation suite that follow the evolution of molecular clouds, while resolving individual stars and including all gas and feedback physics. The two runs have different initial conditions, one is a periodic box with driven turbulence (Box), while the other is an isolated cloud without turbulent driving (Sphere). We find that the ρ-PDF for both runs is initially well-fit by a log-normal (LN) plus a power-law (PL) function. However, as the SFR peaks, the PDF for the Sphere run becomes well-fit by just a wide LN. Conversely, the Box run PDF remains well-fit by a LN+PL function for the entirety of the run.

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1. Introduction

Studies predict that in a turbulent supersonic medium, i.e., in a star-forming cloud, the density probability distribution function (ρ-PDF) has a lognormal (LN) shape (Vazquez-Semadeni 1994). This can be understood by invoking the Central Limit Theorem which establishes that when random variables are added, the shape of their distribution tends toward a normal distribution. In a turbulent supersonic medium, shocks cause random, multiplicative changes in density, so in log-space, the density PDF is a normal distribution (Molina et al. 2012). However, these clouds also experience gravity, which has been shown to lead to the development of a power-law (PL) tail at high densities in both observations (Kainulainen et al. 2009) and simulations (Federrath & Klessen 2013). In this work, we analyze two runs from the STARFORGE[5] simulation suite that follows the evolution of star-forming clouds, while resolving individual stars and including all relevant stellar feedback physics (i.e., jets, radiation, winds, supernovae, see Grudić et al. 2021). Both runs initially contain $2\times10^4\ M_\odot$ gas but start out from different initial conditions (IC). The first starts as a uniform density sphere with velocities following a Gaussian random field, embedded in pressure equilibrium within diffuse gas (Sphere IC). The second starts as a "stirred" periodic box (Box IC) with continuous turbulent driving through its evolution (similar to Federrath et al. 2014). The simulations follow the evolution of the clouds until stellar feedback destroys the clouds. In this work we focus on the evolution of the shape of the volume ρ-PDF and its relation to the star formation rate (SFR).

2. Methods

We fit the shape of the ρ-PDF with a piece-wise function, $p(\rho)$, using least squares fitting. $p(\rho)$ consists of two components, a LN part below the ρ_t transition density, and a PL part above ρ_t, specifically

$$\frac{dV}{d\ln\rho} \sim p(\rho) \equiv \begin{cases} \frac{C}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(\ln\rho/\bar{\rho}-s_0)^2}{2\sigma^2}\right) & \rho < \rho_t \\ \mathcal{N}C\rho^{-\beta} & \rho \geqslant \rho_t, \end{cases} \quad (1)$$

where ρ is the density of gas with $\bar{\rho}$ being the mean value, σ is the width of the LN, C is the normalization constant and β is the slope of the PL. Note that s_0 can be expressed with σ and that the constants ρ_t and $\mathcal{N}$ are chosen so that $p(\rho)$ is continuously differentiable, see Equations (19)–(21) in Burkhart (2018). This leaves σ and β as the only free parameters (apart from normalization). Note that when fitting the ρ-PDF of the Sphere runs we only fit above the density of the diffuse medium the sphere is embedded in.

3. Results and Discussion

We find in both cases that the ρ-PDF is well-fit by a LN+PL shape in the early phases of star formation, with a roughly constant σ width. During this early phase, the slope of the PL tail is also roughly constant at around 0.7 and close to the analytically predicted value of 0.54 (Girichidis et al. 2014). However, for the Sphere run, as feedback becomes dominant (coinciding with the SFR peak), σ increases and the entire ρ-PDF becomes well-fit by a single, wide LN without a PL tail (see Figure 1). Meanwhile, the Box run is well-described by a LN+PL shape with roughly constant parameters throughout the simulation.

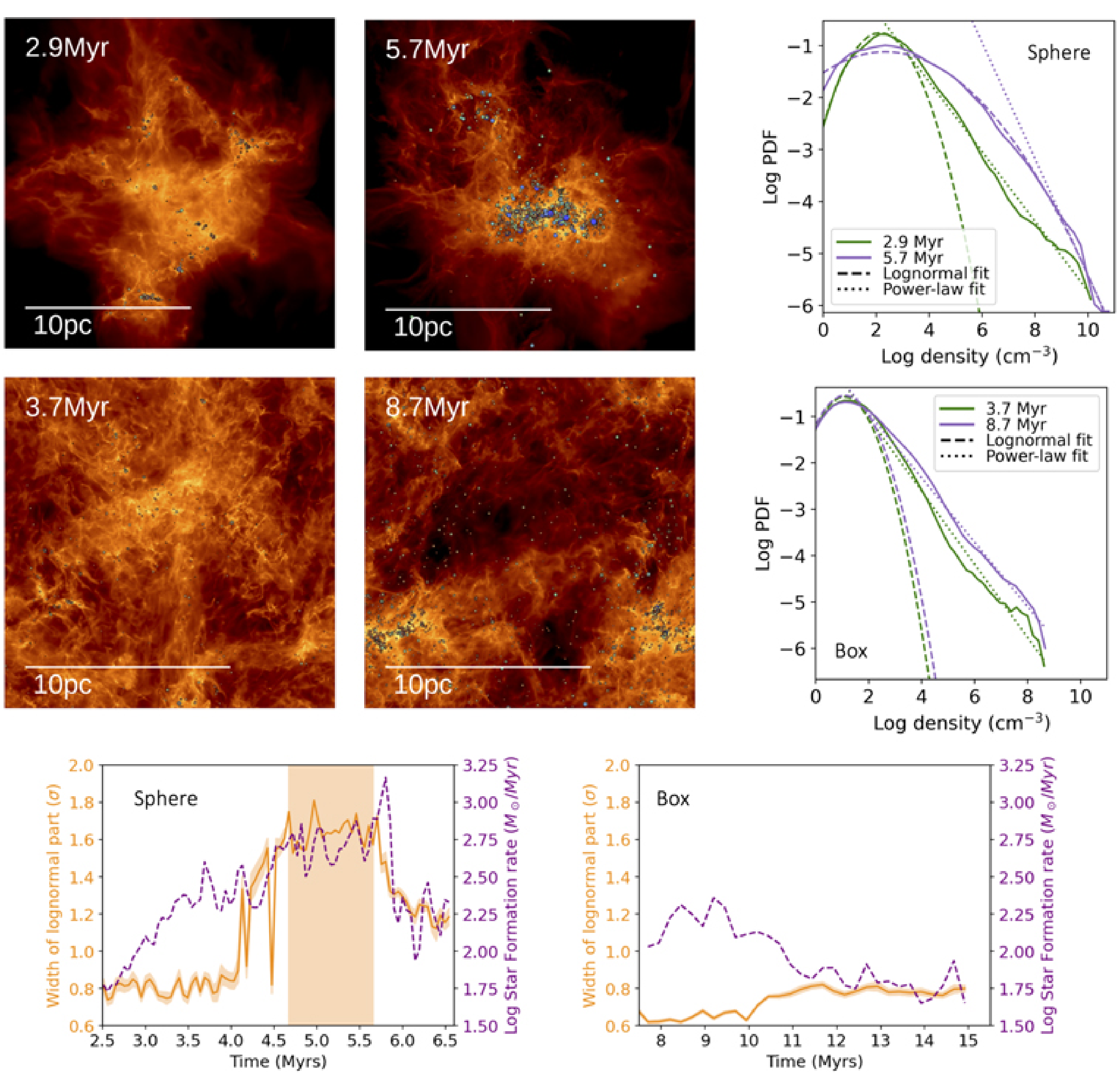

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Figure 1. Top row: surface density maps of the Sphere run at different times, as well as the corresponding fitted ρ-PDFs. Middle row: same as the top row but for the Box run. Bottom left: evolution of the star formation rate in the Sphere run and the width of the LN part, the shaded region indicates the error of the fit, which eventually becomes extremely large as the ρ-PDFs is no longer well-fit by a LN+PL. Note that the abruptness of the transition is an artifact of the fitting, the transition to fully LN is more gradual. Bottom right: evolution of the star formation rate in the Box run and the width of the LN part, showing roughly constant values throughout the star-forming phase.

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Observed star-forming clouds are islands of molecular gas embedded in the ISM like the Sphere run, but also experience external driving, like the Box run. Thus, their behavior must lie somewhere between these two simulations and neither result can be used to completely describe reality. Note that most of the star formation occurs in the Sphere run when the PDF is not well-fit by a LN+PL, so the scope of analytic theories relying on a PDF of that shape (e.g., Burkhart 2018; Jaupart & Chabrier 2020) do not apply to all possible star formation scenarios.

Footnotes

5 http://www.starforge.space

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