Enhanced Star Formation Rate in a Self Gravitating Turbulent Molecular Cloud

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INTRODUCTION

•It is a well-known fact that the density probability distribution function (PDF) of an isothermal turbulent flow without self gravity is fitted with a log-normal function (e.g, Vazquez-Semadeni et al. 1994; Padoan et al. 1997; Scalo et al. 1998; Passot & Vazquez-Semadeni 1998; Nordlund & Padoan 1999; Ostriker et al. 1999, 2001, Nordlund & Padoan 2002).

•Because of this fact, the log-normal density PDF becomes one of the important ingredients of star formation theories regulated by turbulence (Padoan & Nordlund 2002; Krumholz & McKee 2005). Star formation rates are estimated based on the log-normal density PDF (Elmegreen 2002, 2003; Krumholz & McKee 2005; Wada & Norman 2007).

•However self-gravity of gas enhances the fraction of density PDF at a higher density range compared with the log-normal distribution (Vazquez-Semadeni et al. 2008).

•The motivation of this presentation is to show larger enhancement of star formation rate by self-gravity than that based on the log-normal density PDF.

•For this purpose, we performed a turbulent, isothermal MHD simulation with self-gravity. We found that the density PDFs calculated from the simulation are enhanced at the higher density range compared with the log-normal distribution. The enhanced density PDFs result in higher star formation rates.

NUMERICAL METHOD

•We simulate core formation in a turbulent molecular cloud.

•For this purpose we integrate the following isothermal MHD and Poisson equations.

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{v})=0 \qquad \rho\left(\frac{\partial\mathbf{v}}{\partial t}+\mathbf{v}\cdot\nabla\mathbf{v}\right)+\nabla\left(\rho a^2\right)-\frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B}=0$$

$$\frac{\partial\mathbf{B}}{\partial t}-\nabla\times(\mathbf{v}\times\mathbf{B})=0 \qquad \nabla\cdot\mathbf{B}=0 \qquad \nabla^2\Phi=4\pi G\rho$$

•There are two parameters if we write the above equations in dimensionless units: one is the plasma β=1, which is the ratio of gas pressure to magnetic pressure, and the other is the Jeans number J=4, which is the ratio of the one dimensional size of a computational box L, to the Jeans length λ_{J0}. with mean density.

•In order to generate turbulence we put an equal amount of kinetic energy per time in to the system. The power spectrum of the random Gaussian perturbation for each velocity component has the following form,

$$P(k)=\delta v^2(k)\propto k^6\exp\left(-\frac{8k}{k_{pk}}\right),\ k_{pk}=2\left(\frac{2\pi}{L}\right)$$

where L is the one-dimensional size of the computational box (Stone et al. 1998, Mac-Low 1999). The one-dimensional rms Mach number is about 17 in a converged state.

•Initially the computational box contains uniform density and uniformly magnetized medium. The periodic boundary condition is used.

•The simulation was done using a MHD TVD code (Kim et al. 1998). The number of cells used is 512^3.

RESULTS

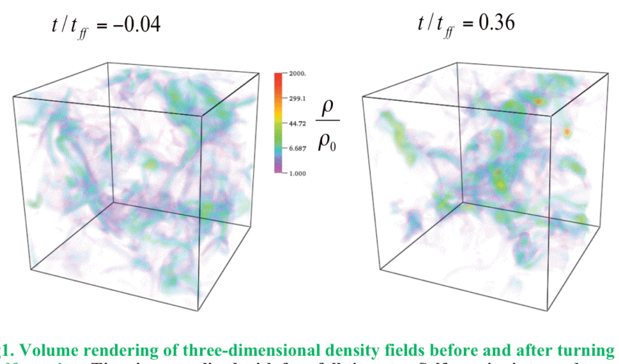
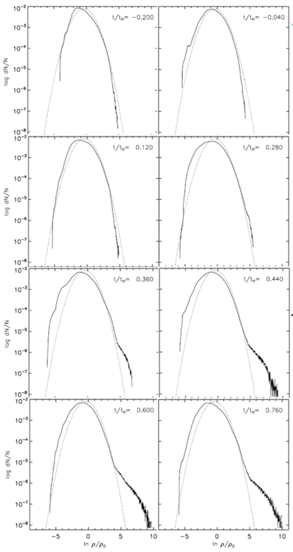


Fig1. Volume rendering of three-dimensional density fields before and after turning on self-gravity. Time is normalized with free-fall time, t_{ff}. Self-gravity is turned on at t=0. Colors represent density normalized with an initial density, ρ_0. A color bar is included. Right before turning on self-gravity (left rendering), there is very little gas with yellow color and no gas with red color. However, $t=0.36t_{ff}$ (right rendering) there are quite many condensations who colors are yellow and red. It is this condensations that actually increase SFR_{ff} (star formation rate per free-fall time).



volution of density PDF. In each panel, time is given in units of free-fall time and a density PDF at that time is plotted with a solid line. Again self-gravity was turned on at t=0. A dotted line is a fit of a density PDF averaged over a saturated stage of turbulence before turning on self-gravity with a log-normal function,

$$p_{LN}(x)=\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left[-\frac{(y-\mu)^2}{2\sigma^2}\right];$$

$$y=\ln\left(\frac{\rho}{\rho_0}\right);\ \mu=-\frac{\sigma^2}{2}$$

μ = -0.68, σ=1.16. We plotted the same dotted line on all the panels. The log-normal fit to a density PDF at, for example, t/t_{ff}=0.760 is almost same as the dotted line. As time goes on after turning on self-gravity, the volume fraction of the density PDF at a higher density range has been increased. It is this increased fraction that resulted in SFR_{ff} that is much larger than the one estimated based on the log-normal distribution.

We then measured (dimensionless) core formation rate per free-fall time, CFR_{ff}, which is defined by the following relation (Krumholz & McKee 2005),

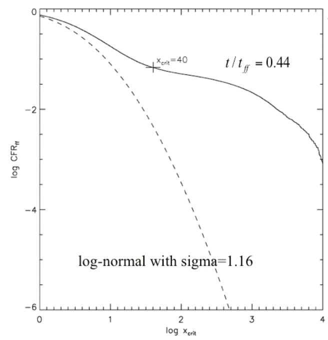
$$CFR_{ff}=SFR_{ff}(\varepsilon_{core}=1,\phi_t=1)=\int_{x_{crit}}^{\infty}xp(x)dx$$

where $x=\rho/\rho_0$ and p(x) is a density PDF. The x_{crit} is normalized density at which the sonic scale is equal to the Jeans length at that density. It is determined by the relation,

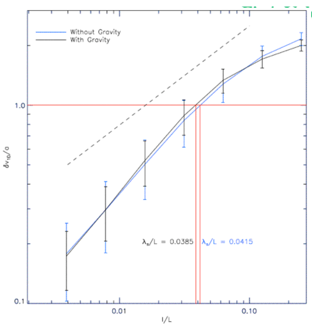
$$\lambda_J(x_{crit})=\frac{\lambda_{J0}}{\sqrt{x_{crit}}}=\lambda_s$$

For λ_{J0}=L/4, λ_s=0.04L (see Fig4), x_{crit}=40. If p(x) is a log-normal function, then CFR_{ff} can be calculated analytically (Mrumholz & McKee 2005) measured in the above,

$$CFR_{ff}=1+\mathrm{erf}\left(\frac{-2\ln(x_{crit})+\sigma^2}{2^{3/2}\sigma}\right)$$



R_{ff} as a function of x_{crit}. The dotted line is the CFR_{ff} calculated with the above error function with σ=1.16. The solid line is the CFR_{ff} calculated with a bumped density PDF (a solid line on the panel labeled with t/t_{ff}= 0.44 in Fig2). This figure clearly shows that CFR_{ff} with self-gravity significantly larger than that calculated with the log-normal distribution. At x_{crit}=40 that is determined from the condition of $\lambda_J=\lambda_s$, CFR_{ff} with self-gravity is about one-order-magnitude larger than CFR_{ff} with the log-normal distribution.



ocity dispersion vs. size relation. The horizontal axis is the size of a small box normalized with the size of the whole computational box. The vertical axis is the one-dimensional velocity dispersion normalized with the sound speed. For the given size of a small box, we took 100 random positions and calculate the mean and standard deviation of velocity dispersions. Black and blue solid lines are the relation at times without and with self gravity, respectively. They are almost coincidnet with each other. The dotted line has a slope of 0.5, which is a typical power index of Larson's relation. The measured sonic scale, λ_s=0.04L, at which the velocity dispersion is equal to the sound speed.

CONCLUSIONS

•The fraction of density PDF, obtained from a simulation with self gravity, at a higher density range is significantly larger than that of the log-normal density PDF.

•The star (core) formation rate per free-fall time calculated from the enhanced density PDF is significant larger than that calculated with the log-normal density PDF.