SF2A 2015
F. Martins, S. Boissier, V. Buat, L. Cambrésy and P. Petit (eds)

THE SUPERNOVA-DRIVEN INTERSTELLAR MEDIUM

O. Iffrig[1] and P. Hennebelle[1, 2]

Abstract. Stellar feedback is thought to be responsible for the regulation of star formation in the interstellar medium. In particular, supernovae inject a significant amount of energy and momentum into the ISM. However, the dynamical range of length scales swept by supernovae are too large to be handled at once with current computational resources. We present a two-step study: first we performed numerical simulations of a single supernova event inside a turbulent cloud, which then enabled us to extract a sub-grid model for larger-scale simulations of stratified disk-like structures. In the latter case, we focus on the influence of supernovae on the properties of the gas, namely turbulence and star formation. We also emphasize the strong dependence with respect to the employed sub-grid feedback scheme.

Keywords: ISM: supernova remnants, ISM: structure, turbulence, stars: formation

1 Introduction

1.1 Context

Star formation rates estimated by assuming a gravitational collapse within a few free-fall times are several orders of magnitude higher than the observed star formation rates (Zuckerman & Evans 1974; Dobbs et al. 2014). Therefore, other physical processes are involved in regulating star formation. Three main processes have been considered efficient: magnetic field (Shu et al. 1987), turbulence (Mac Low & Klessen 2004) and stellar feedback (e.g. Agertz et al. 2013). While a substantial magnetic field intensity has been measured in molecular clouds (Crutcher 2012), its influence remains too weak to explain the difference. Thus, turbulence and stellar feedback are believed to contribute significantly. However, turbulence decays quickly (Mac Low & Klessen 2004), therefore it has to be driven, either by large-scale structure such as spiral arms, or by stellar feedback. Thus, stellar feedback has a double role in the dynamics of the ISM: on the one hand it regulates star formation by injecting energy into the gas, and on the other hand it drives turbulence, which in turns regulates star formation.

Motivated by these results, we studied the impact of one of the most energetic stellar feedback processes, namely supernovae. We first quantified the momentum injected into the interstellar medium by a supernova, before running self-consistent simulations at larger scale, checking the influence of the feedback scheme. Then, motivated by a seemingly consistent feedback model, we perform high-resolution runs to study the properties of the supernova-driven interstellar medium. The next subsection presents the numerical code we use and some technical features. The following section shows the results of cloud-scale (a few parsecs) simulations of one single supernova event (Iffrig & Hennebelle 2015), the following one the results of kiloparsec-scale simulations of a supernova-regulated galactic disk, and the last section concludes this discussion.

1.2 Numerical method

To perform the numerical simulations, we used the RAMSES code (Teyssier 2002). It is a second-order Godunov code solving the magnetohydrodynamics (MHD) equations with self-gravity, using a constrained transport scheme for the magnetic field (Fromang et al. 2006). We also used a cooling function accounting for both the various cooling processes relevant to the ISM (Sutherland & Dopita 1993; Wolfire et al. 2003; Audit &

[1] Laboratoire AIM, Paris-Saclay, CEA/IRFU/SAp – CNRS – Université Paris Diderot, 91191 Gif-sur-Yvette Cedex, France
[2] LERMA (UMR CNRS 8112), Ecole Normale Supérieure, 75231 Paris Cedex, France

Hennebelle 2005), and a UV background heating model, leading to a cooling function similar to the one used in Joung & Mac Low (2006).

The equations we solve are:

$$\partial_t \rho + \vec{\nabla} \cdot (\rho \vec{v}) = 0, \tag{1.1}$$

$$\partial_t (\rho \vec{v}) + \vec{\nabla} \cdot \left(\rho \vec{v} \otimes \vec{v} + \left(P + \frac{B^2}{8\pi} \right) \vec{I} - \frac{\vec{B} \otimes \vec{B}}{4\pi} \right) = -\rho \vec{\nabla} \phi, \tag{1.2}$$

$$\partial_t E + \vec{\nabla} \cdot \left(\left(E + P - \frac{B^2}{8\pi} \right) \vec{v} + \frac{1}{4\pi} \vec{B} \times \left(\vec{v} \times \vec{B} \right) \right) = -\rho \vec{v} \cdot \vec{\nabla} \phi - \rho \mathcal{L}, \tag{1.3}$$

$$\partial_t \vec{B} - \vec{\nabla} \times \left(\vec{v} \times \vec{B} \right) = 0, \tag{1.4}$$

$$\Delta \phi - 4\pi G \rho = 0, \tag{1.5}$$

where ρ, $\vec{v}$, P, $\vec{B}$, ϕ, E and $\mathcal{L}$ respectively being the density, velocity, pressure, magnetic field, gravitational potential, total (kinetic plus thermal plus magnetic) energy and cooling function.

Supernova feedback is injected at chosen time and location, either from pre-defined values, or depending on the evolution of the supernova. The details will be given in the next sections. Ejecta, momentum and (kinetic and thermal) energy are injected directly around the chosen location in one single time step. The injection radius is chosen to be a sphere of at least two computing cells.

Sink particles (Krumholz et al. 2004) are used in the self-consistent disk simulations in order to track star formation sites. One massive star is assumed to be formed when a sink has accreted more than 120 $M_\odot$. This threshold is used to trigger supernova feedback in the fiducial scheme.

The turbulent initial conditions are generated using an analytic density profile and a random velocity field sampled with a power-law Kolmogorov spectrum with random phase distribution. A constant magnetic field is imposed within the whole box. The simulation starts by letting the gas evolve to a self-consistent state where turbulence is fully developed.

2 Single supernova simulations

First, we ran simulations to quantify the momentum injected by a supernova into the interstellar medium. The detailed results are shown in Iffrig & Hennebelle (2015). This study served as a basis for the larger-scale simulations.

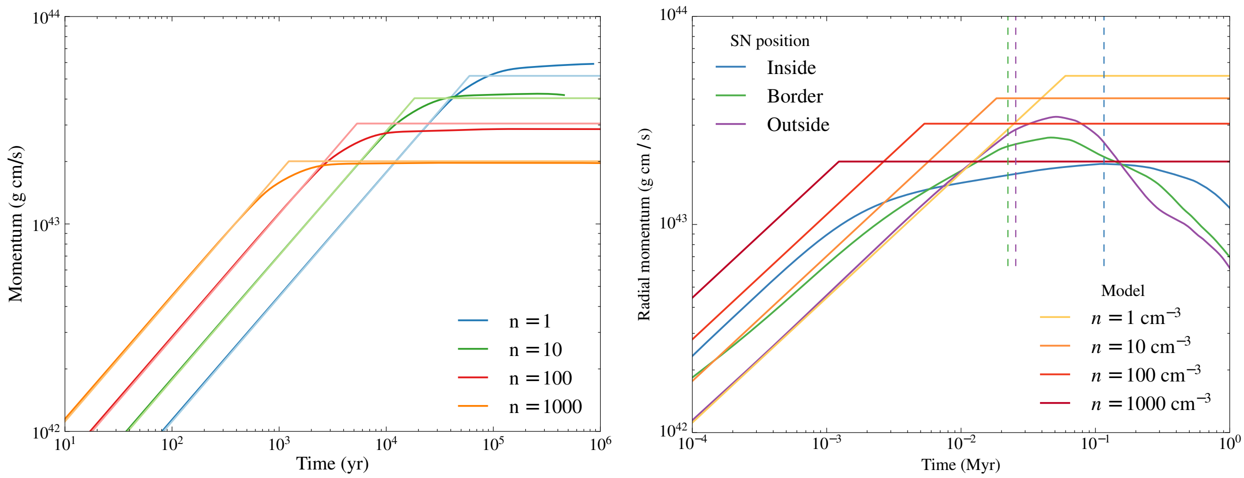

Fig. 1. Integrated radial momentum injected by a single supernova. **Left:** Supernova in a uniform medium for different ambient densities. **Right:** Supernova in a turbulent cloud-like medium.

Box size (pc)	Density (cm^{-3})	Temperature (K)
160	1	4907.8
80	10	118.16
80	100	36.821
40	1000	19.911

n_0 (cm^{-3})	t_{tr} (10^4 yr)	p_f (10^{43} g cm s^{-1})
1	2.99	5.18
10	0.919	4.04
100	0.267	3.04
1000	0.0616	2.01

Table 1. Left: Initial conditions for the uniform runs. The gas is initially at rest. **Right:** Transition time t_{tr} and final momentum p_f as a function of the ambient density n_0, estimated with the model.

2.1 Uniform density runs

We first assessed our scheme by running three-dimensional simulations of a supernova in a uniform medium. We were able to reproduce the well-known supernova remnant evolution models (e.g. Oort 1951; Sedov 1959; Chevalier 1974; Cioffi et al. 1988; Blondin et al. 1998), and derived a simple model from these. The simulation results are consistent with the model.

We simulated the explosion of a supernova in densities of 1, 10, 100 and 1000 cm^{-3}. The temperature is chosen so that the gas is at thermal equilibrium with respect to the heating and cooling processes. The simulation box size is chosen so that the remnant does not escape the box. The values of these parameters are summarized in Table 1 left. We inject 10^{51} erg of thermal energy at the center of the simulation box.

According to the Sedov-Taylor (Sedov 1959) model, the radial momentum of the supernova remnant can be expressed as

$$p_{43} = 1.77\ n_0^{1/5} E_{51}^{4/5} t_4^{3/5}, \tag{2.1}$$

where p_{43} is the total momentum in units of 10^{43} g cm s^{-1}, n_0 is the particle density in cm^{-3}, E_{51} is the supernova energy in units of 10^{51} erg, and t_4 is the age of the remnant in units of 10^4 yr.

We define the transition time t_{tr} as the moment when the age of the remnant becomes equal to the cooling time τ_{cool} of the shell which is given by

$$\tau_{cool} = \frac{3}{2} k_B \frac{n_s T_s}{n_s^2 \Lambda_s}, \tag{2.2}$$

where n_s and T_s are the gas density and temperature of the shell, and Λ_s the net cooling (in erg cm^3 s^{-1}). This transition time corresponds to the transition from the Sedov-Taylor adiabatic phase to a momentum-conserving snowplow (Oort 1951). We do not take into account the pressure-driven snowplow stage (Cioffi et al. 1988) because it does not change the final momentum significantly, and is not distinguishable from the transition between the two other stages we consider.

To model analytically the second stage, we solve numerically the equation $t_{tr} = \tau_{cool}$. For the highest ambient densities ($n_0 \gtrsim 10$), the momentum injection is reasonably well fitted by the momentum-conserving snowplow model with the final momentum p_f taken to be the momentum of a Sedov-Taylor blast wave at $2t_{tr}$ (the numerical values are given in Table 1 right). Some small deviations are found with the lowest density case because the pressure within the shell is still higher than the surrounding pressure and the shell keeps accelerating. When the surrounding gas density varies by 3 orders of magnitude, the total momentum varies by a factor of about 3. The injected radial momentum in the simulations is shown on Figure 1 left. The results are consistent with the model and confirm this weak dependency.

2.2 Turbulent runs

The interstellar medium being highly turbulent (e.g. Hennebelle & Falgarone 2012), it presents large density contrasts which may strongly affect the dynamics of a supernova remnant sweeping through it. Thus, we needed to simulate a more realistic cloud-like medium which is expected to exist in the vicinity of an exploding star. To achieve this, we generate a cloud-like medium from a spherically symmetric density distribution

$$\rho(r) = \frac{\rho_0}{1 + \left(\frac{r}{r_0}\right)^2} \tag{2.3}$$

where $\rho_0 = 9370$ cm^{-3} and $r_0 = 1.12$ pc. The total mass enclosed in this cloud is 10^4 $M_\odot$. The cloud is surrounded by a halo of density $\rho_0/100$, mimicking the H_I halo around molecular clouds. A turbulent velocity field is added on top of this density distribution to generate a turbulent medium where gravity and turbulence contain the same energy. This cloud is surrounded by uniform 1 cm^{-3} medium at thermal equilibrium. We let the cloud evolve for 1.25 Myr (roughly 1 crossing time) in order for the turbulent fluctuations to build up. Then, a supernova is injected at a chosen location, as shown in Figure 2. The three runs referred to as "Inside", "Border" and "Outside" correspond to supernovae exploding in ambient densities of 700, 20 and 1.2 cm^{-3}.

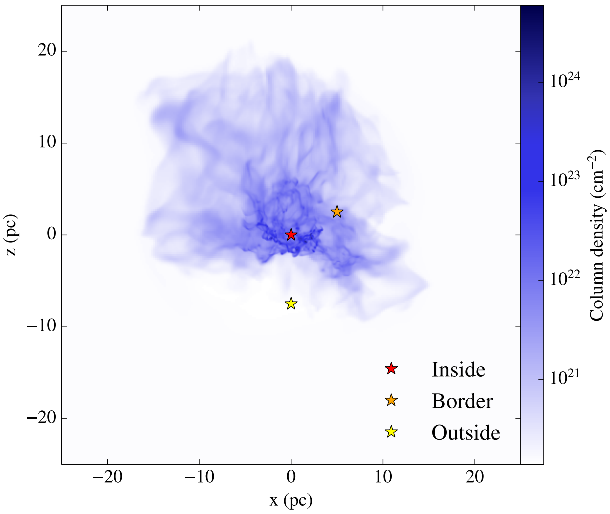

Fig. 2. Positions of the supernovae in the simulated cloud.

We calculated the radial momentum (with respect to the location of the supernova) injected by the explosion. The results are shown in Figure 1 right. Despite a slightly different evolution, the injected momentum is coherent with the trends given by the model. Especially, the final momentum has the predicted order of magnitude of 10^{43} g cm/s. The decrease of the momentum at late times corresponds to matter flowing out of the simulation box.

It is worth noting that most of the gas expelled from the cloud has a low to intermediate (less than 100 cm^{-3}) density, although a supernova inside the cloud is able to push denser gas too. The evolutions of mass and momentum for different density thresholds are shown in Figure 3 and Figure 4. A supernova may therefore not prevent star formation efficiently, but has some significant effects on the intermediate density gas, which would otherwise have collapsed later on by the effect of gravity.

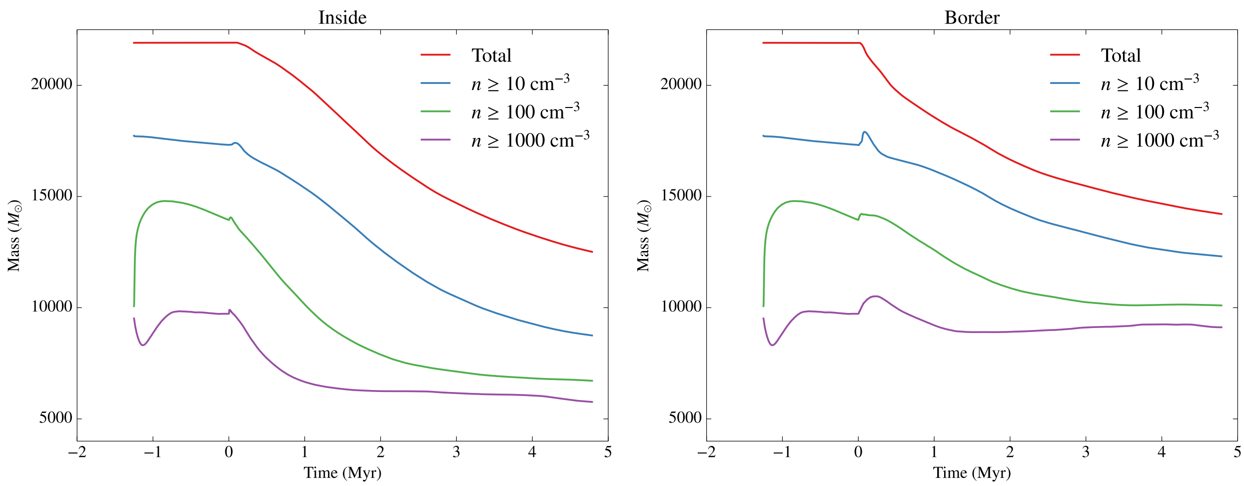

Fig. 3. Evolution of mass for different density thresholds as a function of time. **Left:** Supernova inside the cloud. **Right:** Supernova at the border of the cloud. The dashed lines correspond to the first outflow from the simulation box.

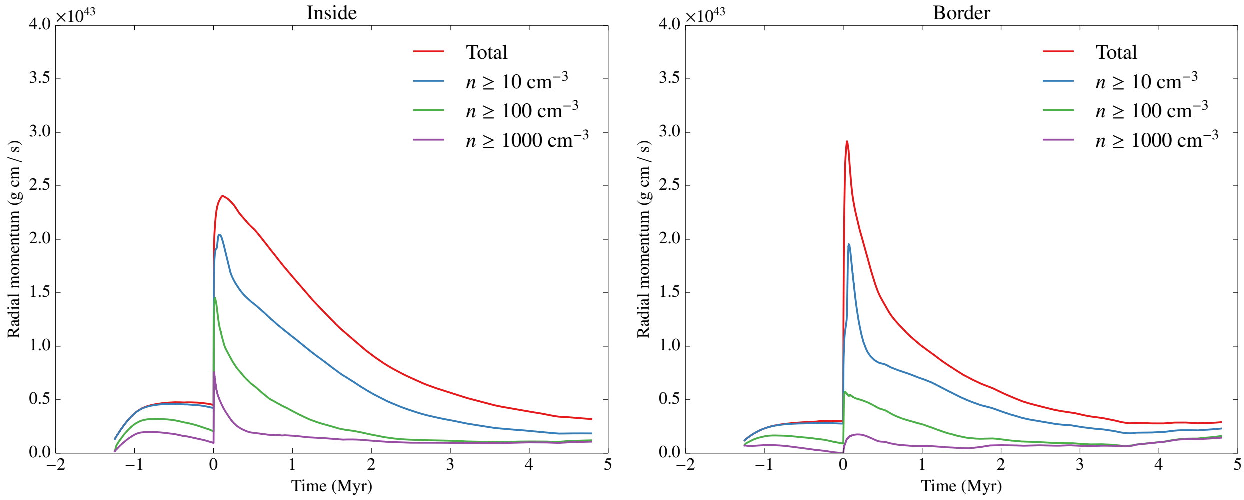

Fig. 4. Evolution of radial momentum for different density thresholds as a function of time. **Left:** Supernova inside the cloud. **Right:** Supernova at the border of the cloud.

2.3 *Summary*

Based on the standard supernova remnant evolution models, we were able to derive a simple model for the injection of momentum into the interstellar medium. We successfully compared it to the results of simulations of a uniform medium swept up by a supernova remnant, as well as those of a more realistic environment. The model gives us a simple prescription of a few 10^{43} g cm/s momentum injected for an initial energy of 10^{51} erg, almost regardless of the surrounding density. The precise distribution of this momentum to the gas strongly depends on the location of the explosion: if the supernova happens inside a cloud, the bubble will be pushing the dense gas around it until it can escape through more diffuse chimneys. A supernova exploding outside a cloud will mainly push lower-density gas, and thus cannot prevent immediate star formation, but still injects sufficient energy and momentum to prevent ~ 100 cm^{-3} gas to collapse.

This model is, however, useful as sub-grid physics for a larger-scale simulation where supernovae are injected self-consistently with respect to star formation sites. The next section presents our tests of this model in simulations of a part of a galactic disk.

3 Large-scale study of a stratified galactic disk with supernova feedback

The previous study of the momentum injected by a supernova into cloud-like medium, and also its emphasis on the sensitivity to the correlation between supernovae and star formation sites triggered our interest for self-consistent simulations. We considered a 1 kpc simulation cube containing a stratified galactic disk with an initially gaussian density profile

$$n(z) = n_0 \exp\left(-\left(\frac{z}{z_0}\right)^2\right) \tag{3.1}$$

with $n_0 = 1.5$ cm^{-3} and $z_0 = 150$ pc. The temperature is initially set to 8000 K, which corresponds to warm neutral gas. A turbulent velocity field is imposed on this initial condition, as described in Section 1.2. We also added a mean-field gravitational potential accounting for the distribution of stars and dark matter

$$g(z) = -\frac{a_1 z}{\sqrt{z^2 + z_0^2}} - a_2 z \tag{3.2}$$

with $a_1 = 1.42 \times 10^{-3}$ kpc Myr^{-2}, $a_2 = 5.49 \times 10^{-4}$ Myr^{-2} and $z_0 = 180$ pc, as used by Joung & Mac Low (2006). We performed simulations on a 256^3 grid to test different feedback schemes (for more detailed results, see Hennebelle & Iffrig 2014), before scaling up to 1024^3 for our fiducial scheme (see below).

The supernova energy is injected as kinetic (momentum) and thermal energy, using the prescriptions of 10^{51} erg energy and 2×10^{43} g cm/s momentum. These quantities are distributed in a sphere of at least 2 computational cells.

3.1 Scheme

In order to assess the importance of the correlation between supernovae and star forming regions, we ran several simulations with different feedback prescriptions. For the simplest one (referred to as "random"), we use a uniform distribution in the galactic plane, a gaussian distribution in altitude, and a fixed rate of $1/50\ \mathrm{yr}^{-1}$ in time. The second one has the same rate in time, but with a correlation to the densest point in the simulation.

The more realistic runs use sink particles to track star-forming regions, and we assume there is one supernova per 120 $M_\odot$ of accreted gas. In order to assess the correlation between the supernova and the location of the sink, we used two schemes. The fiducial one (referred to as "sphere") puts the supernova randomly in a sphere of 10 pc around the sink. The second one (referred to as "shell") puts the supernova farther away, that is in a shell between spheres of 10 pc and 20 pc respectively.

As expected, there are strong differences between the results of these runs. Figure 5 shows column density maps for the various schemes. Without feedback, the gas quickly collapses due to gravity, forming dense filaments. A randomly distributed feedback causes a big gas dispersion, but does not prevent run-away gravitational collapse. The fiducial scheme is able to ensure an equilibrium between star formation and gravitational collapse. Finally, a correlation with more distance between the sink particles and the supernovae entails very efficient feedback which effectively prevents star formation, but completely destroys the disk structure.

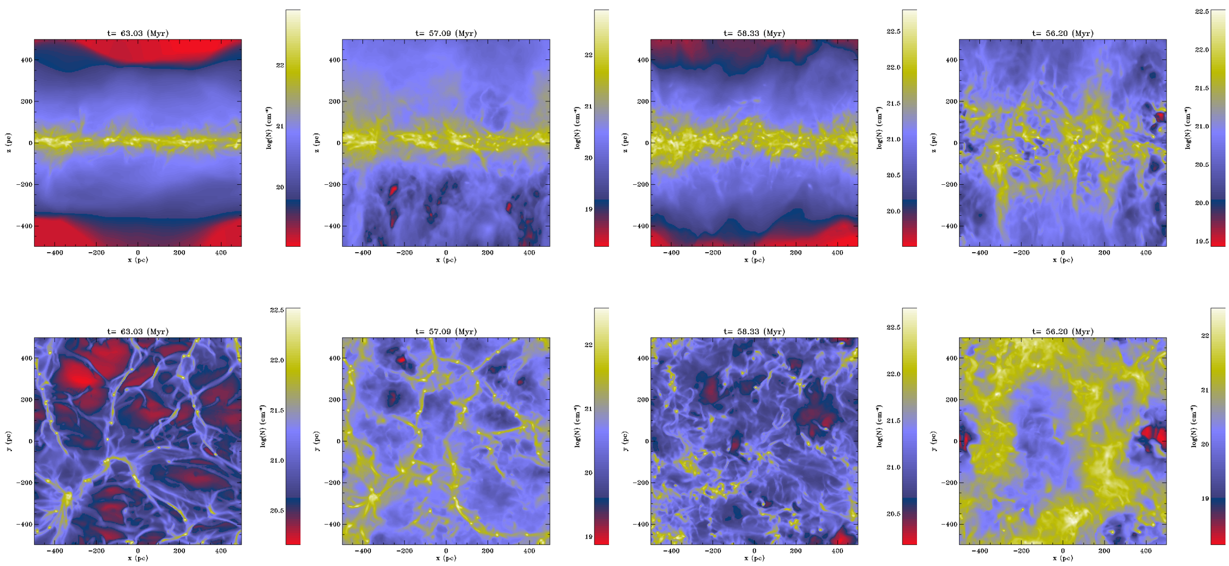

Fig. 5. Column density maps of the galactic disk simulations for different feedback schemes. **From left to right:** no feedback, random, sphere, shell. **Top:** Edge-on view. **Bottom:** Face-on view.

3.2 Star formation

The star formation efficiency can be estimated by tracking the mass accreted by sinks throughout the simulation. The absolute results have to be handled very carefully, but they provide at least a means of comparing the impact of each feedback scheme on star formation. The results are summarized in Figure 6. We observe that correlated feedback is indeed able to reduce star formation rate by a factor around 10, but since the evolution seems to be still out of equilibrium, this factor may still decrease. These results put forward the "sphere" scheme as our fiducial scheme, for it is able to sustain a vertical equilibrium as well as to regulate star formation. Note however that supernova feedback alone does not explain all of the discrepancy between observed star formation rates and estimations based on gravitational collapse.

3.3 Turbulence

The fiducial scheme being successfully assessed, we performed a higher resolution run in order to study in more details the properties of the supernova-driven interstellar medium. We scaled the resolution down to 1 pc, using

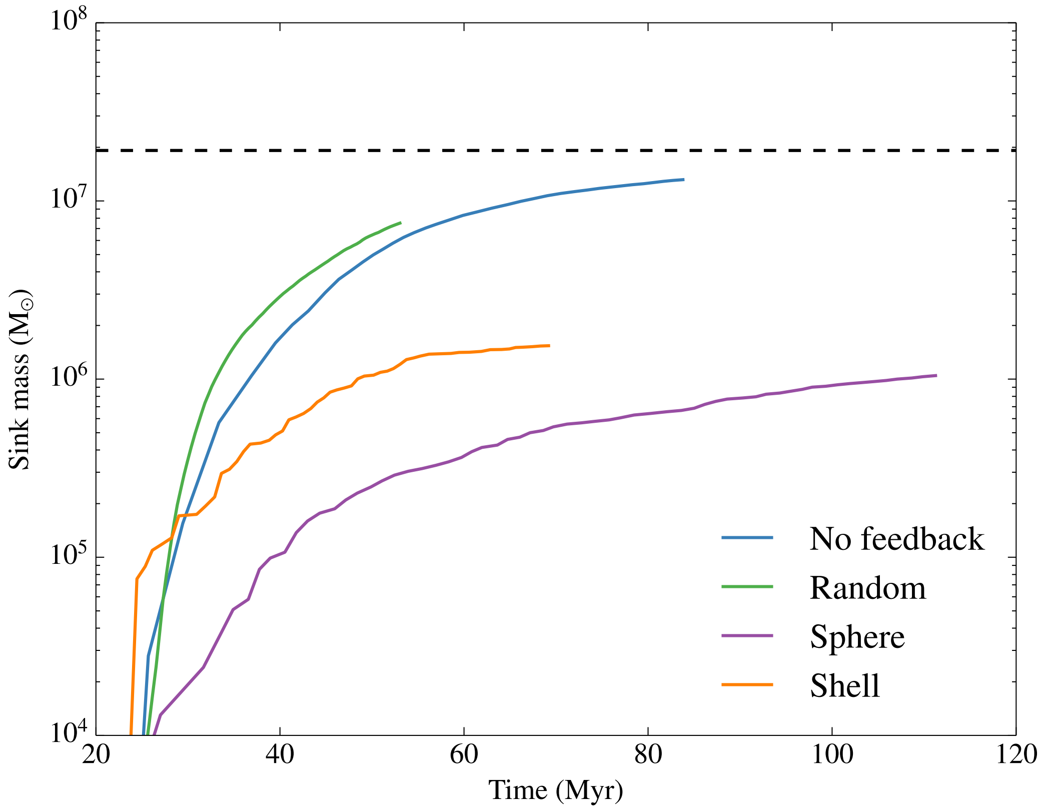

Fig. 6. Star formation efficiency, as measured with the total mass accreted by sink particles. The dashed line corresponds to the initial gas mass.

a 1024^3 uniform grid. This grid enables us to compute power spectra to quantify the properties of turbulence. A column density map of our fiducial run with enhanced resolution is shown on Figure 7.

Given this 1 pc resolution, we calculated Fourier power spectra of several physical quantities, plotted on Figure 8, and compared them to well-known models of turbulence (e.g. Kolmogorov 1941; Fleck 1996; Kritsuk et al. 2007). Given the artificial viscosity introduced by the numerical scheme, the smallest scales are not reliable to derive physical conclusions (see Kritsuk et al. 2007, and references therein for more details). However, there is a small inertial range showing power-law behaviour coherent with the predictions of Kolmogorov (1941) and Fleck (1996) with a compression degree $\alpha = 1/6$. The injection scale is not clearly appearing because the simulations do not include any large scale forcing: the turbulence is sustained by the supernovae.

4 Conclusions

We performed simulations of supernovae exploding in both uniform and turbulent medium. With help of the uniform medium simulations, we derived a simple prescription for the momentum a supernova should inject into the surrounding gas. The simulations of a single supernova interacting with a molecular cloud confirm the validity of this prescription, although the precise dynamics strongly depend on the relative location of the supernova and the cloud, making clear the need of self-consistent simulations.

Using these results, we studied the influence of the feedback scheme in self-consistent simulations of a 1 kpc cube of a galactic disk. The study shows important variability with respect to the scheme. A correlation between supernovae and star formation sites seems to be enough to maintain a vertical equilibrium, also decreasing the star formation rate significantly, but not enough to explain the big discrepancy between observed star formation rates and the rates corresponding to gravitational collapse acting alone. This result is however bound to change because supernovae are not the only significant feedback process. Stellar winds and radiation happen before supernovae and inject a similar energy into the surrounding medium. Therefore, taking them into account may further reduce the star formation rate, explaining the remaining difference.

The high resolution runs performed allow us to quantify the properties of a supernova-driven interstellar medium. This medium exhibits power spectra compatible with well-known turbulence models. A further study (in preparation) will provide more detailed results on the structure of the simulated medium.

References

Agertz, O., Kravtsov, A. V., Leitner, S. N., & Gnedin, N. Y. 2013, ApJ, 770, 25
Audit, E. & Hennebelle, P. 2005, A&A, 433, 1
Blondin, J. M., Wright, E. B., Borkowski, K. J., & Reynolds, S. P. 1998, ApJ, 500, 342
Chevalier, R. A. 1974, ApJ, 188, 501
Cioffi, D. F., McKee, C. F., & Bertschinger, E. 1988, ApJ, 334, 252
Crutcher, R. M. 2012, ARA&A, 50, 29
Dobbs, C. L., Krumholz, M. R., Ballesteros-Paredes, J., et al. 2014, Protostars and Planets VI, 3
Fleck, Jr., R. C. 1996, ApJ, 458, 739
Fromang, S., Hennebelle, P., & Teyssier, R. 2006, A&A, 457, 371
Hennebelle, P. & Falgarone, E. 2012, A&A Rev., 20, 55
Hennebelle, P. & Iffrig, O. 2014, A&A, 570, A81
Iffrig, O. & Hennebelle, P. 2015, A&A, 576, A95
Joung, M. K. R. & Mac Low, M.-M. 2006, ApJ, 653, 1266
Kolmogorov, A. 1941, Akademiia Nauk SSSR Doklady, 30, 301
Kritsuk, A. G., Norman, M. L., Padoan, P., & Wagner, R. 2007, ApJ, 665, 416
Krumholz, M. R., McKee, C. F., & Klein, R. I. 2004, ApJ, 611, 399
Mac Low, M.-M. & Klessen, R. S. 2004, Reviews of Modern Physics, 76, 125
Oort, J. H. 1951, in Problems of Cosmical Aerodynamics, 118
Sedov, L. I. 1959, Similarity and Dimensional Methods in Mechanics
Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23
Sutherland, R. S. & Dopita, M. A. 1993, ApJS, 88, 253
Teyssier, R. 2002, A&A, 385, 337
Wolfire, M. G., McKee, C. F., Hollenbach, D., & Tielens, A. G. G. M. 2003, ApJ, 587, 278
Zuckerman, B. & Evans, II, N. J. 1974, ApJ, 192, L149

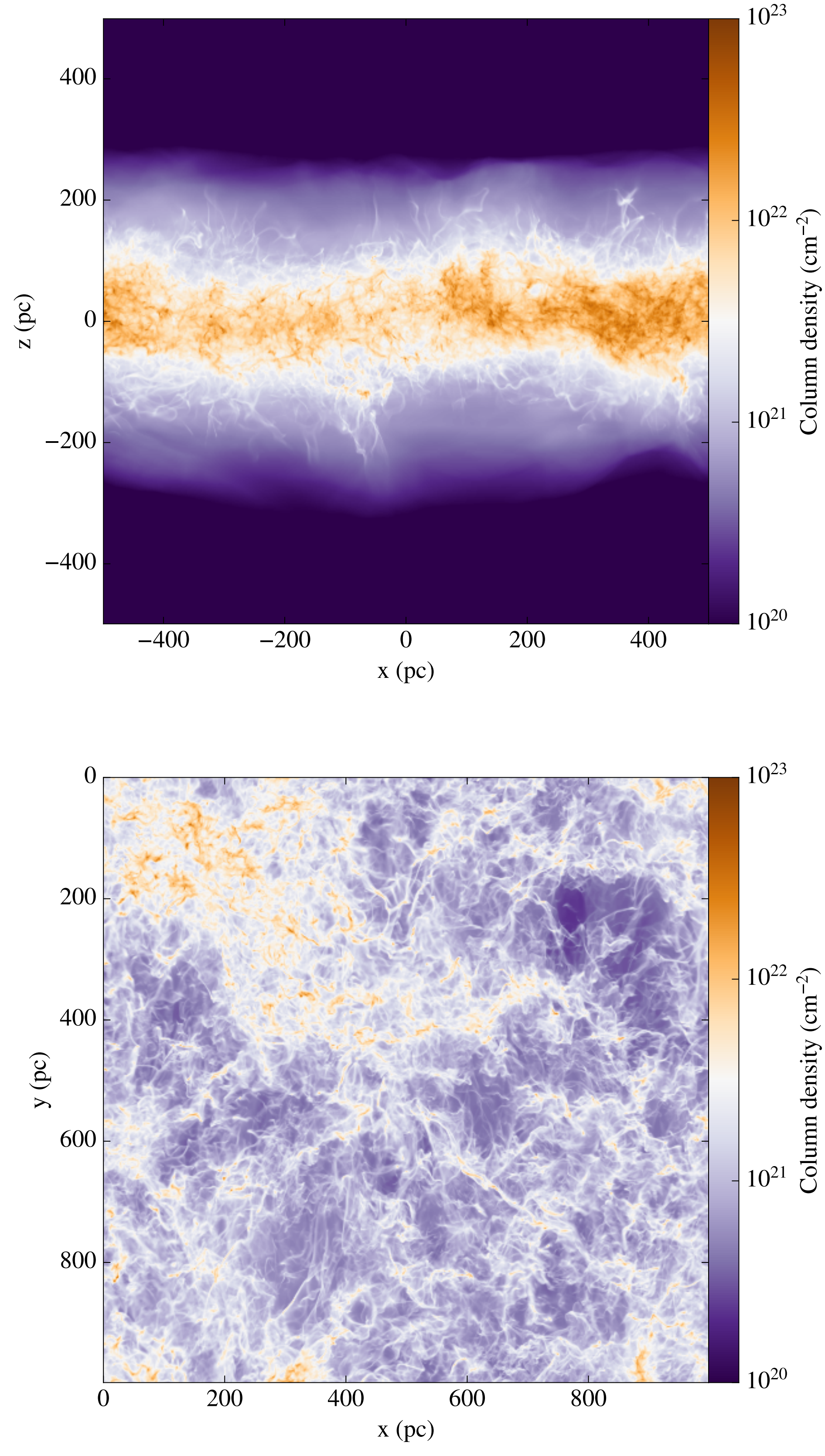

Fig. 7. Column density maps of the high-resolution fiducial run. **Top:** edge-on view. **Bottom:** face-on view.

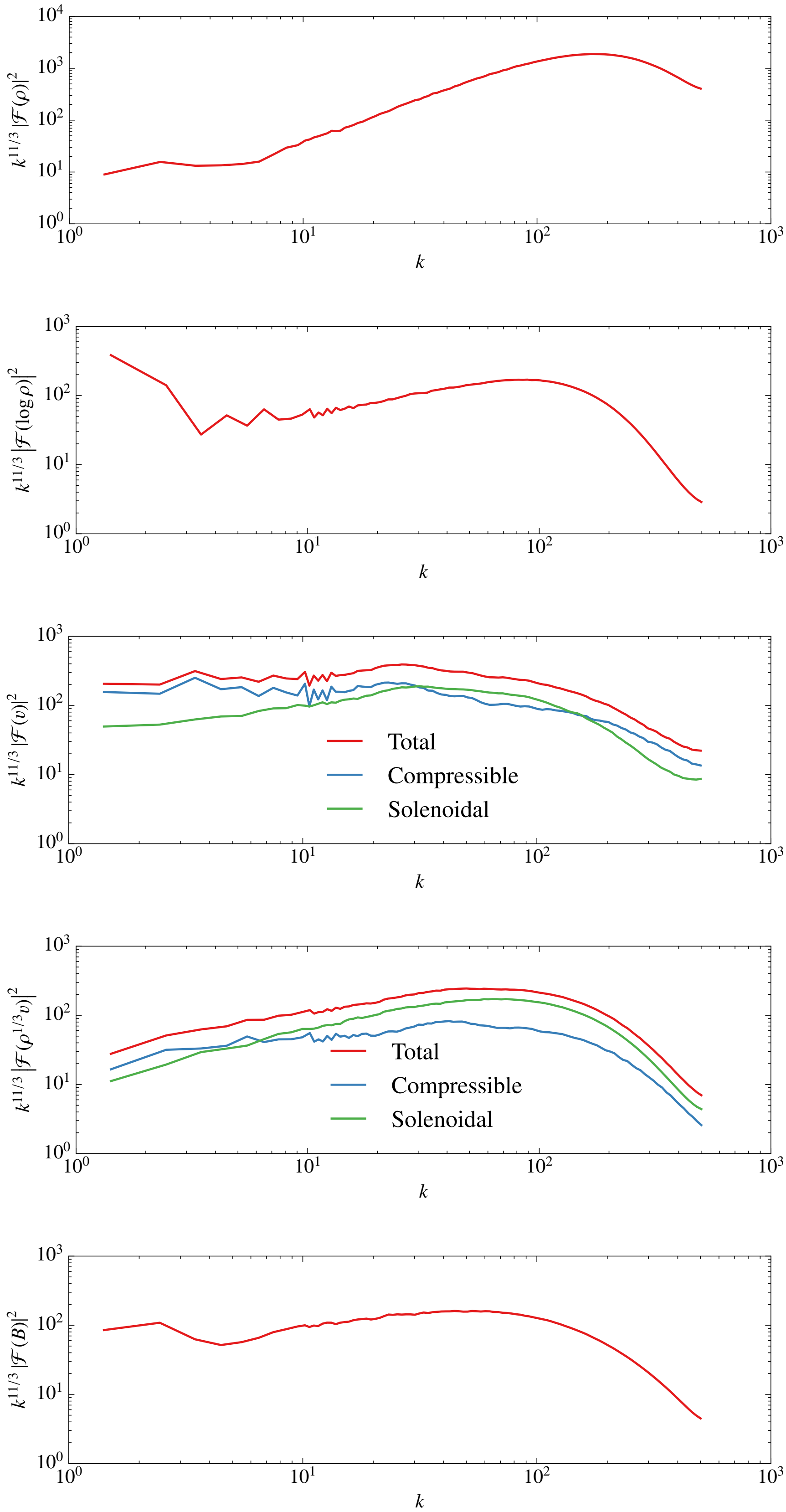

Fig. 8. Power spectra for the disk simulations. **From top to bottom:** density, log. density, velocity, density-weighted velocity (see Kritsuk et al. 2007), magnetic field. The power spectra are compensated by $k^{11/3}$, so a purely Kolmogorov spectrum would appear flat.