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A Local Three-dimensional Model of the Supernova-regulated ISM

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Abstract. We use a local three-dimensional non-ideal MHD model to investigate the effects of supernova explosions on the ISM in the solar neighbourhood. Our model includes supernova heating, galactic differential rotation, magnetic fields, vertical gravity and parameterized radiative cooling of the ISM. The model gives a plausible representation of the hot and warm phases of the ISM.

1. Introduction

Supernovae (SNe) heat, accelerate and compress the ISM, driving shock waves. They provide the dominant source of interstellar turbulence and produce a hot component of the ISM as discussed by e.g. Cox & Smith (1974) and McKee & Ostriker (1977). The three-phase model of McKee & Ostriker (1977) suggests that the filling factor of the hot component is rather large ($f = 0.70$). Recently it has been argued (e.g. Slavin & Cox 1993) that the filling factor could be smaller. With smaller filling factors the expected configuration would be such that the hot gas would be confined to isolated bubbles or chimneys (Mac Low & McCray 1988; Norman & Ikeuchi 1989). In the present paper we use numerical magnetohydrodynamic (MHD) simulations to calculate the filling factor of the hot component in the solar neighbourhood.

2. The model

We model the ISM in the solar neighbourhood using a local three-dimensional non-ideal MHD model, that includes the effects of vertical gravity, compressibility, magnetic fields, heating via supernova explosions, radiative cooling of the ISM and large scale shear due to the galactic differential rotation. We adopt a local Cartesian frame of reference, which rotates on a circular orbit with radius R and angular velocity Ω_0 about the galactic centre, with x, y and z corresponding to the radial, azimuthal and vertical directions, respectively. We solve the standard non-ideal MHD equations, namely the uncurled induction equation for the magnetic vector potential, the momentum equation, the energy equation and the continuity equation. SN heating and radiative cooling are modelled by source and loss terms in the energy equation.

SNe are modelled as instantaneous explosive events releasing thermal energy. The energy is fed into the system via a localized heating term (per unit volume) of the form $\Gamma = \xi(\mathbf{r}, t)\, E_{\rm SN}$, where $\xi(\mathbf{r}, t)$ is a random function ($\xi \neq 0$ in a small volume V during an energy release event and zero otherwise; ξ is normalized such that $\int \xi \, d^3r \, dt = 1$), $E_{\rm SN}$ is the explosion energy of a single event; the energy is released during only one timestep, which is typically about 100 years or less. The probability of a SN explosion at a given position is proportional to the excess of density above a certain threshold $\rho_* = 4 \times \rho_0$, where ρ_0 is the initial gas density at the midplane. In the vertical direction we assume an exponential distribution of SNe with a scale height $H_{\rm SN}$. Supernova heating is balanced by radiative cooling, where the cooling function is adopted from Dalgarno & McCray (1972) and Raymond et al. (1976). This cooling function does not allow any thermally unstable phases at $T < 10^5$ K. A detailed description of the code is given by Nordlund & Stein (1990) and Brandenburg et al. (1995).

3. Results and discussion

We have performed the following calculations. The size of the computational domain is $L_x = L_y = 0.5$ kpc in the radial and azimuthal directions and $L_z = 2$ kpc in the vertical direction. The corresponding mesh size is $63 \times 63 \times 254$. The adopted supernova parameters are $E_{\rm SN} = 10^{51}$ erg, $\sigma_0 = 1.2 \times 10^{-5}\,{\rm yr}^{-1}\,{\rm kpc}^{-2}$ for the explosion rate per unit area, and $H_{\rm SN} = 250$ pc. The value of $H_{\rm SN}$ adopted here may be an overestimate, but this does not affect the temperature and density of the ISM phases obtained below. For the ISM we take $\rho_0 = 0.1\,{\rm cm}^{-3}$, $H = 100$ pc, $T_0 = 10^4$ K, $\Omega_0 = 25\,{\rm km\,s}^{-1}\,{\rm kpc}^{-1}$ and $B_0 = 0.1\,\mu$G, roughly corresponding to the warm component of the ISM. The initial magnetic field is purely azimuthal and regular. The initial field is chosen to be rather weak to investigate whether or not it can be amplified.

A typical snapshot of a simulation run is presented in the left panel of Figure 1, where we show a three-dimensional volume rendering the density field. With the supernova scale height adopted, most of the SNe go off near the midplane (here we neglect Type I SNe which are more widely distributed in z). Vertical density stratification forces the remnants to expand preferentially in the z-direction, and so they form elongated hot bubbles surrounded by dense and cool shells. Matter is effectively transported upwards by these expanding remnants and the density scale height increases as the gas is heated. During the early stages of the simulation, SN remnants can form well-defined bubbles, because the medium into which they expand is then still relatively homogeneous. As time proceeds the matter in the box becomes more and more inhomogeneous and the remnants are no longer well-defined bubbles. Large irregularly shaped cavities and tunnels of hot gas, shell-like structures and vertical filaments can be seen during the later stages, as is well illustrated in the left panel of Figure 1.

After 10–20 Myr, the system has segregated into two phases (see Figure 1, upper and lower right panels). The probability density functions of both density (upper right panel) and temperature (lower right panel) have well pronounced double-peaked form. The the hot, rarefied gas originates in the hot SN cavities,

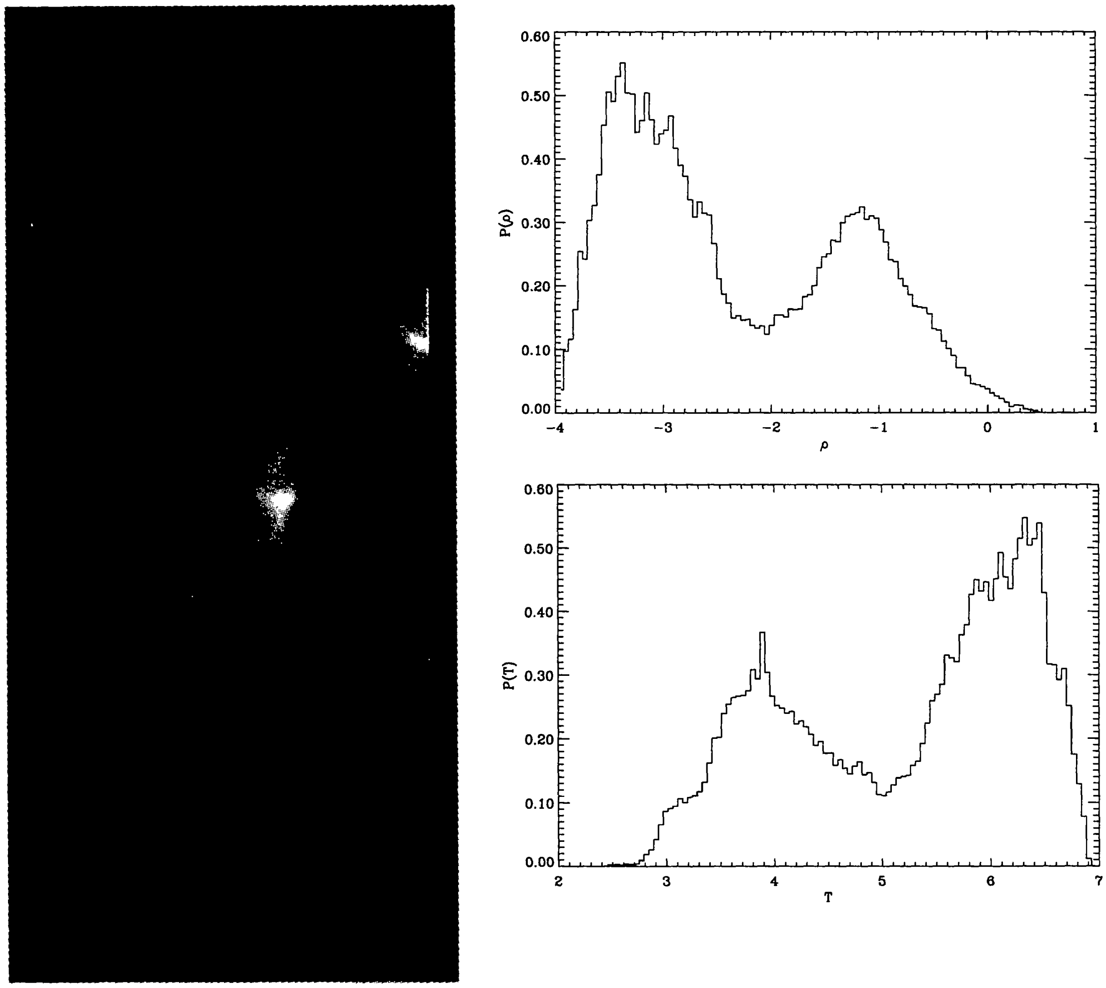

Figure 1. Left panel: a snapshot of the density field at $t = 30$ Myr shown in a box of the size 0.5 kpc $\times$0.5 kpc horizontally and 2 kpc vertically. Lighter shades of grey correspond to higher densities. Upper and lower right panels show the probability density function of density and temperature, respectively.

whereas the cool dense component is due to the cool shells surrounding the hot bubbles. Radiative cooling is especially effective in the dense shells producing even sharper and denser structures. The filling factor of the hot gas ($T > 10^6$ K) averaged over the whole computational domain is $f \approx 0.40$ at a developed state. This value is considerably smaller than the one predicted by McKee & Ostriker (1977), and in our calculations the hot gas remains confined to irregularly-shaped cavities and tunnels. This difference can be quite easily understood: in our model SNe are correlated, i.e. SNe occur only in denser regions, whereas McKee & Ostriker (1977) consider uncorrelated SNe. Our model, in addition, includes radiative cooling, magnetic fields and SN interactions, which all affect the size and shape of the remnants. On the other hand, our filling factor is approximately three times larger than the one obtained from the global model of Ferrière (1998), although the SN parameters used here are almost identical to those in her model (see also Ferrière 1996). There is, however, an important difference in that Ferrière (1998) includes explicitly an additional population of strongly clustered SNe. The filling factor grows with z reaching, in the present simulation, $f = 0.7$–0.8 at $z = 1\,\mathrm{kpc}$.

In our simulations the remnants are often able to break through the disk, as a consequence hot matter and magnetic fields are transported to the halo. Recent 3D MHD calculations of Tomisaka (1998) show that a strong azimuthal magnetic field ($5\,\mu$G) can effectively prevent these break-throughs. In our case, when we start with a considerably weaker initial field, it is justified to ask whether the large number of break-throughs seen in our calculations is due to the unrealistically weak magnetic field. In Tomisaka's model the break-through of the remnants could be prevented only when the scale height of the magnetic field was infinite. In our simulations, however, the semi-width of the initial magnetic field distribution is comparable to the disk scale height and is increasing as time proceeds. In addition, our model includes large-scale shear and turbulence driven by SNe, due to which the magnetic field is amplified and a random component is generated. At the end of our calculations (30–40 Myr) the strength of the magnetic field is of the order of $1\,\mu$G.

In conclusion, our model yields realistic temperature and density for the hot and warm phases of the ISM. These depend only weakly on the model parameters. The filling factor of the hot component is a sensitive function of the SN rate, spatial distribution and clustering. Our simulations describe rapid growth of magnetic field at the scale of the computational domain, which might be an initial stage of the galactic dynamo.

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