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MIXING IN A SUPERNOVA-DRIVEN ISM: A 3-D PARAMETER STUDY

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RESUMEN

Los cocientes de O/H medidos en el medio interestelar (MIE) sugieren una distribución homogenea mientras que los de D/H sugieren que el deuterio está lejos de ser homogeneo. Para estudiar esto, añadimos un campo trazador al modelo de de Avillez (2000) para estudiar la mezcla y dispersión en las simulaciones del MIE a escala de kiloparsecs con distintas tasas de supernovas y distintas escalas de longitud para las inhomogeneidades. Encontramos que la teoría de longitud de mezcla clásica no logra predecir la muy débil dependencia del tiempo de mezcla en la escala de longitud que encontramos a escalas de 25 a 500 pc. Los coeficientes de difusión que derivamos crecen exponencialmente con tiempo en lugar de mantenerse constantes. La variancia de la composición decrece exponencialmente, con una constante de tiempo que depende de la recíproca de la raiz cuadrada de la tasa de supernovas. Una razón principal para estos resultados es que aún cuando la difusión numérica supera los valores físicos, el gas no se mezcla muy rápidamente entre las regiones calientes y frías.

ABSTRACT

Measured O/H ratios in the ISM suggest an homogeneous distribution while D/H suggests that deuterium is far from homogeneous. To study this, we added a tracer field to the ISM model of de Avillez (2000) to study mixing and dispersal in kiloparsec-scale simulations of the ISM with different supernova rates and different inhomogeneity length scales. We find that classical mixing length theory fails to predict the very weak dependence of mixing time on length scale that we find on scales of 25 to 500 pc. Derived diffusion coefficients increase exponentially with time, rather than remaining constant. The variance of composition declines exponentially, with a time constant depending on the inverse square root of the supernova rate. One major reason for these results is that even with numerical diffusion exceeding physical values, gas does not mix quickly between hot and cold regions.

Key Words: **GALAXY: EVOLUTION — GALAXY: GENERAL — GALAXY: STRUCTURE — HYDRODYNAMICS — ISM: STRUCTURE**

1. INTRODUCTION

Measurements of the O/H ratio in the interstellar medium (ISM) by Meyer, Jura, & Cardelli (1998) and Cartledge et al. (2001) suggest that the ISM is well mixed up to heights of 1500 pc. This suggestion is also supported by measurements of O/H ratios in 41 H II regions in M 101 (Kennicutt & Garnett 1996) and in NGC 1569 and 4214 the dispersion is extremely low (Kobulnicky & Skillman 1996, 1997).

However, recent observations using the Interstellar Medium Absorption Profile Spectrograph (IMAPS) suggest that there are local variations in the D/H ratio of up to a factor of three among the studied lines of sight (Jenkins et al. 1999; Sonneborn et al. 2000; York 2002). The detection of deuterium in the ISM indicates that it was not processed into stars and the local variations reported in the D/H ratio suggest incomplete mixing in the ISM.

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Solving this contradiction requires the understanding of how it is possible in a supernova-driven ISM for different species not to be mixed well enough to suppress local variations of their ratio to hydrogen along and among lines of sight. The ISM is regulated by supernova (SN) explosions and, therefore, by well-structured and explosive flows rather than just by diffuse turbulence that acts on the smaller scales. To understand the mixing process in such a medium (and therefore, whether classical mixing length theory can be used to predict the mixing timescales as a function of size scale) we carried out direct numerical simulations of the evolution of the ISM polluted with inhomogeneities of different length scales.

2. MODELING

2.1. *Model*

This is a modified version of the three-dimensional, SN-driven, ISM model of de Avillez (2000), which includes a fixed gravitational field provided by the stars in the disk, radiative cooling (using Dalgarno & McCray 1972, with an ionization fraction of 0.1 for $T < 10^4$ K and a cut-off at 10 K) assuming optically thin gas in collisional ionization equilibrium, and uniform heating due to starlight (that varies with z and is kept constant parallel to the plane, chosen such as to initially balance radiative cooling at 8000 K). The gas is initially distributed in a smooth disk, taking into account the vertical distribution of the molecular, atomic (cool and warm), ionized, and hot components of the ISM, as summarized in Dickey & Lockman (1990), Reynolds (1987), and Ferrière (1998). SNe Ia, Ib+c, II are included with their observed distributions. The vertical distribution of SNe Ib+c and II depends on whether they are found in OB associations or isolated. Clustered supernovae are set up in locations where the current local density is greater than $10\,\mathrm{cm}^{-3}$ with material still accreting ($\nabla \cdot \mathbf{v} < 0$) and a scale height of 46 pc. The number of stars in the association is determined from the overall mass inside a radius of the finest cell resolution, and using the Salpeter IMF the time interval between successive explosions is obtained. No density threshold is used to determine the location where isolated SNe should occur. Similarly, later SNe in associations are no longer determined by gas density. The rates of SNe are taken from Capellaro et al. (1997).

2.2. *Tracer Fields*

To follow how composition differences mix, we use a tracer field. A tracer field acts as a drop of ink in a fluid. The simulations do not include any physical diffusion term, however, so contrary to what happens in a real fluid or gas, the mixing of the tracer field occurs by numerical diffusion, which will generally be faster and larger scale than the physical diffusion in astrophysical problems. As a consequence, the mixing time of a tracer field in our model provides a rather strong *lower* limit for the timescale of mixing resulting from physical diffusion.

The tracer field is set up initially with values of $C = 0$ and 1 on alternating squares of a checkerboard in the plane of the Galaxy with square sides of $l = 25$, 50 or 500 pc. The 500 pc scale corresponds to a tracer field that fills a quarter of a 1 kpc length square board. The distribution is uniform in the vertical direction; that is, the squares are extended into rectangular solids of uniform composition vertically.

2.3. *Code*

This is a 3-D MHD code using adaptive mesh refinement (AMR) in a block-based structure in combination with Message Passing Interface (MPI) developed by de Avillez (2003). The AMR scheme relies on virtual topologies of CPUs created through MPI calls. When a refinement is required, a block is split into eight new blocks (children). This corresponds to an increase in linear resolution by a factor of two in the new blocks. Each child is associated to a new CPU. The adaptive mesh refinement scheme is based on Berger & Colella (1989) and in Bell et al. (1994). The gas dynamics part of the code uses the piecewise-parabolic method of Colella & Woodward (1984), a third-order scheme based on a Godunov method implemented in a dimensionally-split manner (Strang 1968) that relies on solutions of the Riemann problem in each zone rather than on artificial viscosity to follow shocks.

2.4. *Runs*

The computational domain has an area of $1\,\mathrm{kpc}^2$ and a vertical extension of 10 kpc on either side of the midplane. We use AMR in the layer $|z| \leq 500$ pc. In

(*a*)

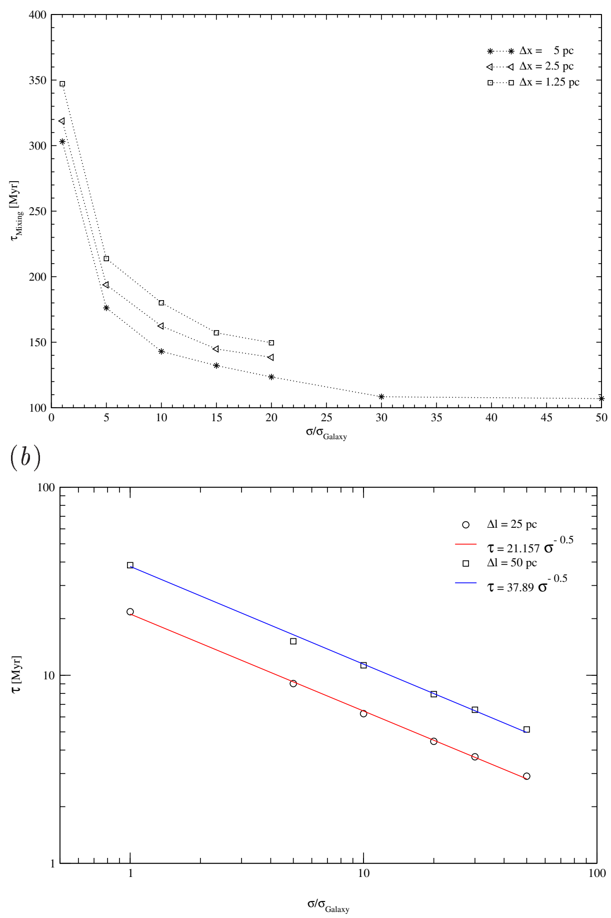

Fig. 1. (*a*) Variation of mixing time of inhomogeneities with $l = 50$ pc with SN rate $\sigma/\sigma_{\rm gal}$ for three finer grid resolutions $\Delta x = 1.25$, 2.5, 5 pc. (*b*) Time variation of the time constant found in the fits for the variance of C for inhomogeneities $l = 25$ and 50 pc.

the highest resolution runs, three levels of refinement are used, yielding a finest resolution of 1.25 pc. For $|z| > 500$ pc the resolution is 10 pc. Periodic boundary conditions are used on the side boundaries, while outflow conditions are used on the top and bottom boundaries. In the current work we report on simulations using seven SN rates $\sigma/\sigma_{\rm gal} = 1$, 5, 10, 15, 20, 30, and 50, having finest grid resolutions of 1.25, 2.5 or 5 pc. A summary of these runs is presented in Table 1 of de Avillez & Mac Low (2002).

3. RESULTS

The main results of this study are: (i) the mixing of a SN-driven ISM is characterized by three regimes: laminar flows dominate on scales close to a kpc, turbulent mixing dominates below about a hundred parsecs, and diffusive processes finally dominate at the smallest scale; (ii) mixing at the larger scales appears nearly independent of the exact value of the diffusive scale, so long as some diffusive process ultimately operates at small scales (Figure 1*a*); classical mixing length theories fail to describe this behavior; (iii) the timescale for complete mixing, providing no further inhomogeneities are introduced, is some 350 Myr for the Galactic SN rate, decreasing with increasing SN rate up to a threshold value. Above this threshold value, further increases in the SN rate have little further effect; (iv) the speed of mixing decreases almost exponentially, with a time constant dependent on the inverse square root of the SN rate (Fig. 1*b*): strong inhomogeities decay quickly, while weaker ones last much longer; (v) the diffusion coefficient derived from fits of a solution of the diffusion equation to the simulation results does not remain constant, as assumed by classical mixing length theory, but rather increases exponentially with time, with a time constant dependent on the SN rate.

4. FINAL REMARKS

At least four issues clearly remain to be addressed. First, we need to determine the actual length scale at which the exponential decrease in tracer field variance ceases, somewhere between 50 and 500 pc. Second, if further inhomogeneities are introduced, such as the chemical elements fed into the ISM by SNe, planetary nebulae, and stellar winds, large parts of the ISM, or indeed the whole ISM, may never reach homogeneity. Third, the simulations do not include the Galactic magnetic field. One can speculate that the presence of magnetic field would contribute to an increase of the mixing timescales in the Galaxy. It could reduce or suppress turbulent flows, and also it would reduce the expansion of laminar flows. We plan to run a new set of simulations to determine dependence of the mixing process on field intensity and distribution. Finally, a theoretical approach, supported by direct numerical simulations, must be developed in order to explain the mixing process in the ISM, because as this work shows, the classical approach to the problem fails.

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