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CLOUD STATISTICS IN NUMERICAL SIMULATIONS OF THE ISM

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RESUMEN

Presentamos resultados preliminares de simulaciones numéricas bidimensionales del balance energético de las nubes del medio interestelar. Mediante el uso de un algoritmo de identificación de nubes, calculamos las energías gravitacional, interna, cinética y magnética de las mismas. Encontramos que, con una dispersión de aproximadamente un orden de magnitud, la energía gravitacional en las nubes es balanceada por las energías restantes. Adicionalmente, y con dispersiones comparables, parece haber equipartición entre las energías cinética y magnética.

ABSTRACT

We present preliminary results on the energy budgets of clouds in two-dimensional numerical simulations of the interstellar medium. Using an automated cloud-identification algorithm, we calculate the gravitational, internal, kinetic and magnetic energies of the clouds. We find that, within a dispersion of roughly one order of magnitude, the gravitational energy in the clouds is balanced by the remaining energies. Furthermore, within the same dispersion, there appears to be equipartition between the kinetic and magnetic energies.

Key words: **ISM: CLOUDS — ISM: KINEMATICS AND DYNAMICS — ISM: STRUCTURE**

1. INTRODUCTION

Interstellar clouds appear to be close to virial equilibrium between the gravitational and other forms of energy (Larson 1981; Myers & Goodman 1988 a,b), even though the assumption that they are in a static equilibrium is highly questionable, as both the clouds and their embedding medium are highly turbulent (e.g., Larson 1981; Hunter & Fleck 1982; Henriksen & Turner 1984; Dickman 1985; Scalo 1987; Falgarone 1989; Fleck 1992). Recently Vázquez-Semadeni, Passot, & Pouquet (1995, Paper I) have suggested that the apparent virialization may be due to nearly-virialized clouds having longer lifetimes, although the flow may not necessarily have a tendency towards forming virialized clouds. In order to test this conjecture, we have initiated a program to produce "surveys" of the clouds that form in numerical simulations of the interstellar medium (ISM) including magnetic fields (Passot, Vázquez-Semadeni, & Pouquet 1995, hereafter Paper II), and to evaluate the various energies and terms in the virial theorem for each cloud.

In this paper we present preliminary results of this work. In § 2 we briefly describe the numerical algorithm and define the relevant quantities. In § 3 we present measurements of the various energies and comparisons that indicate rough equipartition between them. Finally, in § 4 we summarize and discuss the results.

2. THE METHOD

The two-dimensional numerical simulation from which the data are taken represents a square region of 1 kpc on a side of the galactic plane, at roughly the Solar circle. Details on the numerical method can be found in Papers I and II. The simulation gives the time evolution over 1.3×10^8 yr for all relevant physical quantities including the density, velocity, temperature and magnetic field, respectively measured in units of $\rho_0 = 1$ cm^{-3}, $u_0 = 11.7$ km s^{-1}, $T_0 = 10^4$ K and $B_0 = 5$ μG. The gravitational, kinetic, internal and magnetic energies (respectively $E_{\rm g}$, $E_{\rm k}$, $E_{\rm i}$ and $E_{\rm m}$) are defined as:

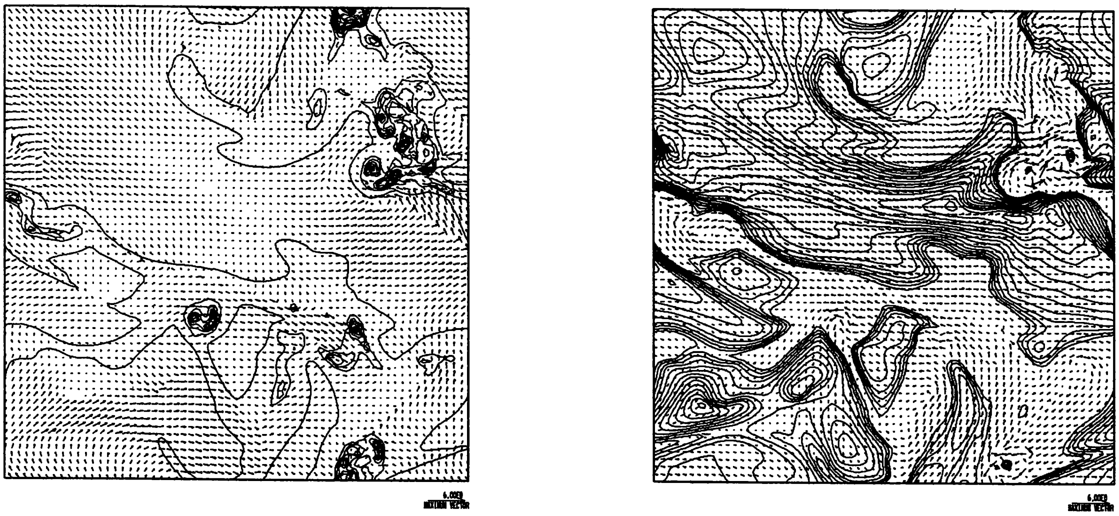

Fig. 1. *Left:* density (contours) and velocity (arrows) fields of the numerical simulation at $t = 6.6 \times 10^7$ yr into the evolution. *Right:* same for the temperature (contours) and magnetic field (arrows). This is a two-dimensional simulation with a resolution of 512 grid points per dimension.

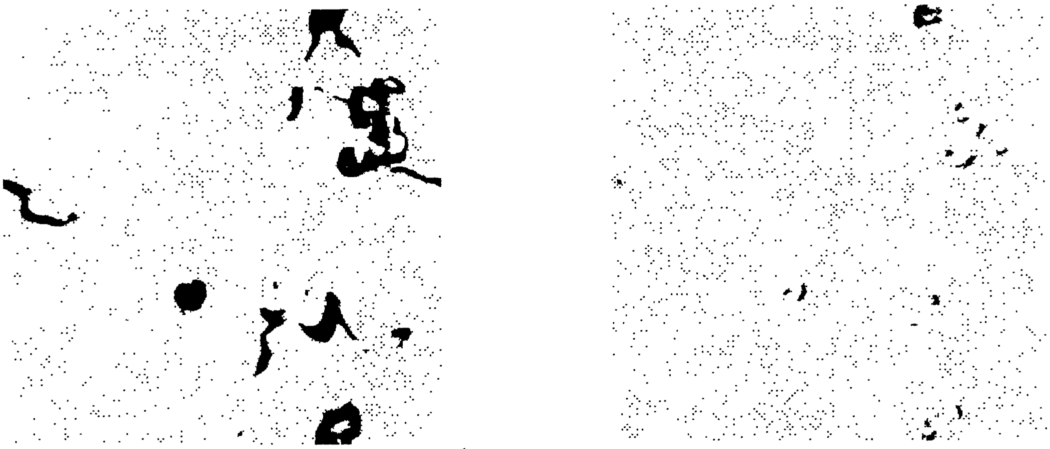

Fig. 2. Masks defining the various clouds at $\rho_{\mathrm{T}} = 4$ (left) and $\rho_{\mathrm{T}} = 16$ (right). The integrals involved in the calculation of the various energies are calculated as sums over the areas defined by the masks.

$$E_{\mathrm{g}} \equiv -\frac{1}{2}\int \rho\phi dV, \qquad E_{\mathrm{k}} \equiv \frac{1}{2}\int \rho|\mathbf{u}|^2 dV, \qquad E_{\mathrm{i}} \equiv \frac{3}{2}\int P dV, \quad \text{and} \quad E_{\mathrm{m}} \equiv \frac{1}{2}\int |\mathbf{B}|^2 dV.$$

In Figure 1 (left) we show the density (contours) and the velocity (arrows) fields at $t = 6.6 \times 10^7$ yr. Similarly, Figure 1 (right) shows the temperature and the magnetic fields. From Figure 1, it is evident that the definition of a "cloud" is somewhat ambiguous, as smaller, denser clouds are hierarchically nested within larger, less dense condensations, as expected for flows in which the local density probability distribution function is independent of the local average density and decays at least exponentially with the fluctuation amplitude (Vázquez-Semadeni 1994). In this paper we adopt a simplistic approach, and define a cloud as a connected set of points whose densities are larger than an arbitrary threshold ρ_{T}.

With this definition, we have developed a numerical algorithm that identifies and labels all clouds, given ρ_{T}, and produces a "mask" file which can be used on all the other fields (Figure 2). This allows us to perform

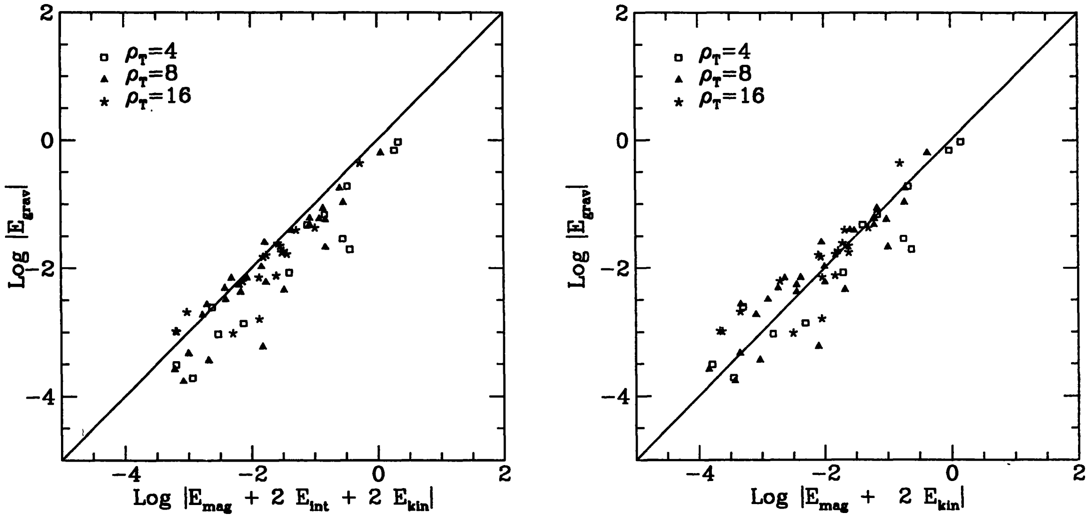

Fig. 3. a) $\log|E_{\rm g}|$ vs. $\log(E_{\rm m}+2E_{\rm i}+2E_{\rm k})$. b) $\log|E_{\rm g}|$ vs. $\log(E_{\rm m}+2E_{\rm k})$

the above integrals inside the exact cloud perimeter and to evaluate the energies for each cloud. A full "survey" is made by taking several values of $\rho_{\rm T}$, in order to include a wide range of cloud sizes. This is equivalent to combining observations obtained with several different tracer molecules. Note also that including clouds defined through various values of $\rho_{\rm T}$ does not amount to including the same cloud several times, since "child" clouds may have substantially different average properties than their "parents". In particular, in the discussion and figures below, we have taken $\rho_{\rm T}=4$ (squares), 8 (triangles) and 16 (stars) (in code units).

3. RESULTS

In Figure 3a we show a plot of $\log|E_{\rm g}|$ vs. $(\log E_{\rm m}+2E_{\rm i}+2E_{\rm k})$, together with the line $\log|E_{\rm g}|=\log(E_{\rm m}+2E_{\rm i}+2E_{\rm k})$. A clear correlation between the gravitational and the sum of the remaining energies is observed, although with a dispersion of roughly an order of magnitude, similar to that found in observational studies (Myers & Goodman 1988b; Falgarone, Puget, & Pérault 1992). Furthermore, it appears that the gravitational energy is systematically too low, and thus, according to this plot, most clouds in the simulation are not gravitationally bound.

However, it is well known (e.g., Shu 1990) that if the pressure is nearly uniform throughout the flow, then the contribution of the internal energy of the cloud is nearly balanced by the external pressure acting on the boundary of the cloud. In the simulation, the typical pressure contrast between clouds and the intercloud medium is ~ 5, except in regions of star formation. The exact contribution of the external pressure requires an integral over the cloud's boundary, which will be discussed in a future paper. In this preliminary report, we show in Figure 3b a plot of $\log|E_{\rm g}|$ vs. $\log(E_{\rm m}+2E_{\rm k})$, which corresponds to the case in which the surface pressure term exactly balances $2E_{\rm i}$. The actual situation must lie between the limiting cases depicted in Figs. 3a and 3b.

In order to search for possible equipartition among different forms of energy, in Figure 4a we show a plot of $\log(E_{\rm m})$ vs. $\log(2E_{\rm k})$, and in Figure 4b we show a plot of $\log(2E_{\rm i})$ vs. $\log(2E_{\rm k})$. A tendency towards equipartition between the turbulent kinetic energy and the magnetic and internal energies is apparent, again with a typical dispersion of roughly an order of magnitude. Note that in Figure 4b a deviation from equipartition seen at low values of the energies is probably an artifact of the simulation, because at small scales the velocity is damped by dissipation.

4. CONCLUSIONS

In this paper we have introduced a simple algorithm for identifying all clouds in numerical simulations of the ISM and presented preliminary statistics over the cloud sample. The gravitational energy appears to be in

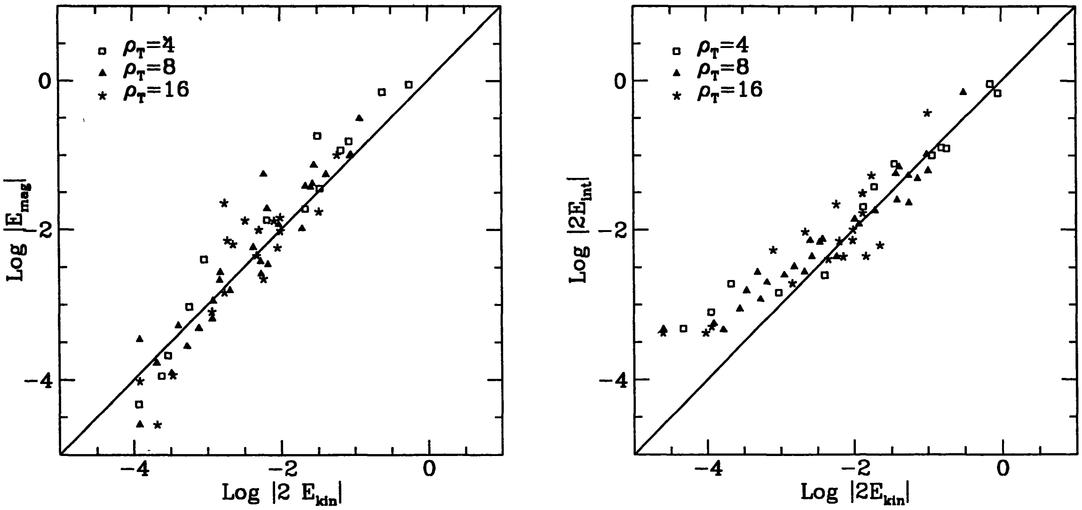

Fig. 4. a) $\log|E_{\rm g}|$ vs. $\log(E_{\rm m} + 2E_{\rm i} + 2E_{\rm k})$. b) $\log|E_{\rm g}|$ vs. $\log(E_{\rm m} + 2E_{\rm k})$

rough balance with the remaining forms of energy, although with non-negligible dispersion. This result is similar to those obtained from observations (e.g., Larson 1981; Myers & Goodman 1988a,b), and has been taken in those works as indicative of near-virialization in clouds. However, we emphasize that the surface terms in the virial theorem may have an important, if not decisive, contribution to the overall virial balance of the clouds, as already suggested by the role of the thermal pressure in the data presented here.

The fact that there seems to be a trend for clouds to exhibit balance between gravity and its opposing agents suggests that the flow may indeed have a tendency towards producing nearly-virial clouds, in contradiction with the conjecture in Paper I. However, the relatively small dispersion about this balance may be an artifact of the low contrast in ρ_T used here due to numerical difficulties. This selects against small, low-density clouds in which gravity is sub-dominant. This difficulty plus the contribution of the surface terms, the necessary modifications to the virial theorem in two-dimensions, and the longevity of clouds as a function of their closeness to virial balance, all need to be assessed before a conclusive answer can be given. Work is currently in progress to address these issues.

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