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THE THERMAL PRESSURE DISTRIBUTION IN THE ATOMIC ISM

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RESUMEN

Presentamos resultados de un estudio numérico sistemático del efecto de las fluctuaciones de velocidad turbulenta en la distribución de presión térmica en flujos térmicamente biestables. Las fluctuaciones se caracterizan por su número Mach 'rms' M relativo al medio tibio y el número de onda de la inyección de energía, $k_{\rm for}$. Nuestros resultados son consistentes con un esquema en que al aumentar alguno de estos paramétros, el cociente local entre los tiempos de cruce turbulento al de enfriamento decrece, produciendo estructuras transitorias con un comportamiento efectivo intermedio entre el equilibrio térmico y el regimen adiabático. Como resultado, el exponente efectivo politrópico $\gamma_{\rm e}$ de las simulaciones queda comprendido entre ~ 0.2 y ~ 1.1, y la presión media del gas difuso generalmente se reduce por debajo de la presión de equilibrio térmico $P_{\rm eq}$, mientras que la del gas denso aumenta respecto a $P_{\rm eq}$. La fracción de zonas de alta densidad ($n > 7.1$ cm^{-3}) con $P > 10^4$ K cm^{-3} aumenta desde cerca de 0.1% a $k_{\rm for} = 2$ y $M = 0.5$ hasta cerca de 70% para $k_{\rm for} = 16$ y $M = 1.25$. Una comparación preliminar con las mediciones de presión recientes de Jenkins (2004) en CI favorece nuestro caso con $M = 0.5$ y $k_{\rm for} = 2$.

ABSTRACT

We present results from a systematic numerical study of the effect of turbulent velocity fluctuations on the thermal pressure distribution in thermally bistable flows. The turbulent fluctuations are characterized by their rms Mach number M (with respect to the warm medium) and the energy injection wavenumber, $k_{\rm for}$. Our results are consistent with the picture that as either of these parameters is increased, the local ratio of turbulent crossing time to cooling time decreases, causing transient structures in which the effective behavior is intermediate between the thermal-equilibrium and adiabatic regimes. As a result, the effective polytropic exponent $\gamma_{\rm e}$ of the simulations ranges between ~ 0.2 to ~ 1.1, and the mean pressure of the diffuse gas is generally reduced below the thermal equilibrium pressure $P_{\rm eq}$, while that of the dense gas is increased with respect to $P_{\rm eq}$. The fraction of high-density zones ($n > 7.1$ cm^{-3}) with $P > 10^4$ K cm^{-3} increases from roughly 0.1% at $k_{\rm for} = 2$ and $M = 0.5$ to roughly 70% for $k_{\rm for} = 16$ and $M = 1.25$. A preliminary comparison with the recent pressure measurements of Jenkins (2004) in CI favors our case with $M = 0.5$ and $k_{\rm for} = 2$.

Key Words: **HYDRODYNAMICS — ISM: STRUCTURE — TURBULENCE**

1. MOTIVATION

The atomic interstellar medium (ISM) is generally believed to be thermally bistable. This property arises because the neutral gas is thermally unstable for 300 K $\lesssim T \lesssim$ 5000 K under the isobaric mode of thermal instability (TI; Field 1965; see also the review by Meerson 1996). The pure development of this instability produces segregation of the gas into two stable phases that can coexist in pressure equilibrium. Also, the ISM is known to be globally turbulent (e.g. Scalo 1987, Franco & Carramiñana, 1999), with velocity dispersions that are transonic with respect to the warm gas ($T \sim 8000$ K), and supersonic with respect to the cold medium ($T \sim 100$ K)(e.g., Heiles & Troland 2003).

The effect of turbulent velocity fluctuations in the development of the isobaric mode of TI has been discussed by Sánchez-Salcedo & al. (2002), Vázquez-Semadeni et al. (2003), Wolfire et al. (2003), and Audit & Hennebelle (2005) among others. The first two of these works noted that velocity fluctuations induce perturbations on the gas that can range from behaving adiabatically, when the turbulent crossing time $\tau_{\rm t}$ across the perturbation size scale is much shorter than the cooling time $\tau_{\rm c}$, to behaving according to the thermal equilibrium condition between cooling and heating, in the opposite limit. The turbulent crossing time, in turn, depends on the scale and amplitude of the velocity fluctuations, and therefore the higher the Mach number, or the smaller the typical scale of the turbulence, the higher the fraction of fluid parcels that are expected to transiently behave closer to an adiabatic regime, and farther away

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from thermal equilibrium. As adiabatic perturbations are linearly stable under the mean conditions of the atomic ISM, Sánchez-Salcedo et al. (2002) and Vázquez-Semadeni et al. (2003) used this to explain the presence of significant amounts of gas with temperatures corresponding to the unstable range. The presence of this gas has been reported in observational (Dickey, Salpeter & Terzian 1977; Kalberla, Schwarz & Goss 1985; Spitzer & Fitzpatrick 1995; Fitzpatrick & Spitzer 1997; Heiles 2001; Heiles & Troland 2003; Kanekar et al. 2003) as well as numerical work (Gazol et al. 2001; Kritsuk & Norman 2002). Audit & Hennebelle (2005) have further quantified the amount of thermally unstable gas, giving a relation between it and the amplitude of the shearing components of the turbulence. Finally, Wolfire et al. (2003) have given an estimate of the ratio of the turbulent crossing time to the cooling time in the warm neutral medium, finding values 0.3–0.9, which led them to suggest that this medium should often exhibit non-equilibrium temperatures.

These results have implications for the thermal pressure PDF in the flow. As a fluid parcel departs from thermal equilibrium, its pressure also departs from the equilibrium value, and we expect a *distribution* of the thermal pressure around its thermal equilibrium value at a given density, determined by the distribution of Mach numbers of the velocity fluctuations. This holds even in the absence of direct local heating.

The thermal pressure distribution varies significantly among different models of the ISM. In the simplest equilibrium multiphase model (Field et al. 1969), the thermal pressure was quasi-uniform and had value determined by thermal equilibrium. The next level of complexity was added by including supernova heating (Cox & Smith 1974; McKee & Ostriker 1977). In particular, the model of McKee & Ostriker (1977) implied a piecewise power-law pressure probability density function (PDF) (Jenkins, Jura & Lowenstein 1983; see also Mac Low et al. 2005), and predicted no pressures below the equilibrium pressure of the warm and cold phases. This model did not consider the local thermodynamic changes in the gas due to the turbulent compressions and rarefactions (advection) that are induced by the energy injection from supernova.

Inclusion of advection is naturally accomplished in numerical models of the star-driven ISM (see Vázquez-Semadeni 2002 for a review). In particular, the recent papers by Mac Low et al. (2005) and de Avillez & Breitschwerdt (2004) have discussed the pressure PDF resulting in their simulations, albeit they appear to obtain different functional forms for it: a lognormal and a distribution closer to a power law, respectively. However, in those simulations it is not possible to disentangle the pressure fluctuations induced purely by turbulent motions, and those due to direct heating from nearby stellar sources.

Observationally, significant pressure fluctuations have been reported in the cold medium. Jenkins et al. (1983) and Jenkins & Tripp (2001) found, using observations of CI, variations greater than an order of magnitude in the cold gas pressure with small amounts of gas at up to $P/k = 10^5$ K cm^{-3}. The latter work additionally found an effective polytropic index for the cold gas $\gamma > 0.9$, which is larger than the $\gamma = 0.72$ derived by Wolfire et al. (1995) for cold gas at thermal equilibrium, mentioning that this could be due to the fact that compressed regions may have a cooling time larger than the dynamical time, so it may behave closer to adiabatically.

In this paper we present results from a numerical systematic study of the effect of turbulent velocity fluctuations, characterized by their rms Mach number M and the energy injection wavenumber, $k_{\rm for}$, on the thermal pressure distribution in a thermally bistable flow. In particular we focus on the effects on the value of the effective polytropic index $\gamma_{\rm e}$, and on the relation between the value of $\gamma_{\rm e}$ and the thermal pressure PDF. We also discuss some implications of our results for previous models and simulations. Full details can be found in Gazol, Vázquez-Semadeni & Kim (2005).

2. RESULTS

We present results from two-dimensional 512^2 hydrodynamic simulations, including the energy equation, of a region of 100 pc on a side, with periodic boundary conditions. For the cooling we use a function with a piece-wise power-law dependence on the temperature, resulting from a fit to the "standard" equilibrium P vs. ρ curve of Wolfire et al. (1995), under the assumption of a constant background heating in thermal equilibrium (Sánchez-Salcedo et al. 2002). The turbulent driving is 100% solenoidal, and is done in Fourier space at a specified wavenumber band around $k_{\rm for}$. Its random amplitude is fixed by a constant injection rate of kinetic energy, which is chosen as to approximately maintain a desired sonic Mach number. This kind of forcing allows to accurately control M and $k_{\rm for}$ and to isolate the effects of velocity fluctuations on the pressure distribution. Our range of parameters is $0.5 \leq M \leq 1.25$ and $2 \leq k_{\rm for} \leq 16$, implying forcing scales 50pc $\geq l_{\rm for} \geq$ 6.25pc. In the set of simulations we discuss here,

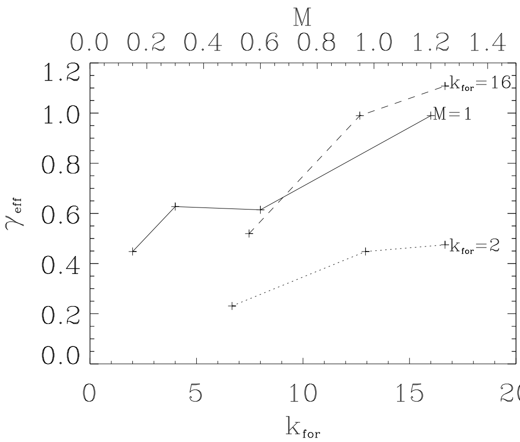

Fig. 1. Least squares slope of the pressure vs. density distributions. The *solid* line shows the variation with the driving wavenumber $k_{\rm for}$, indicated by the lower horizontal axis, at fixed rms Mach numbers $M = 1$. The *dotted* and *dashed* lines show the variation with M, indicated by the upper horizontal axis, at a given $k_{\rm for}$, indicated by the label next to each line.

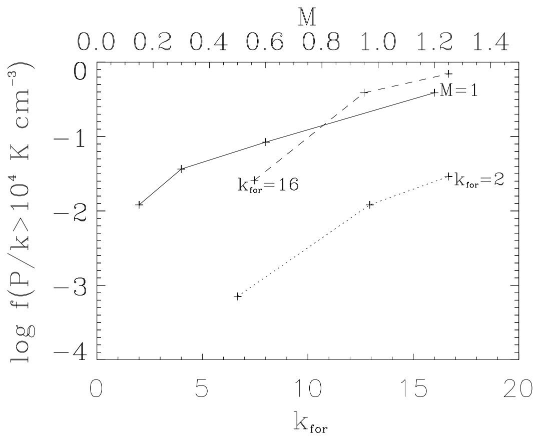

Fig. 2. Fraction of grid cells with $P > 10^4$ K cm^{-3} and for the $n > 7.1$ cm^{-3}. The line coding is as in the figure 1 panel.

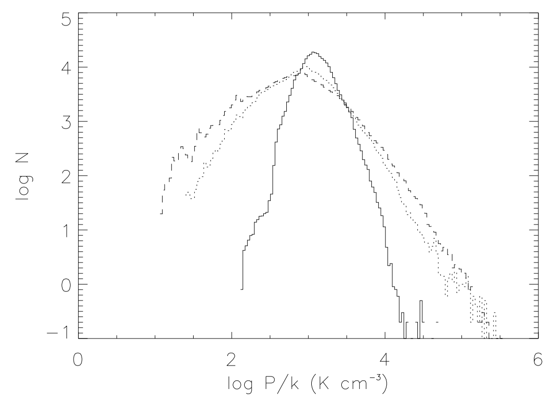

Fig. 3. Total pressure histograms for simulations with $k_{\rm for} = 2$ at $M \sim 0.5$ (*solid line*), $M \sim 1.0$ (*dotted line*), and $M \sim 1.25$ (*dashed line*).

the fluid is initially at rest and in thermal equilibrium with a uniform density and temperature lying in the thermally unstable range ($n_0 = 1$ cm^{-3}, $T_0 = 2399$ K), so that, in the absence of turbulence, the medium would spontaneously segregate into warm-diffuse ($n = 0.34$ cm^{-3}, $T = 7104$ K) and cold-dense ($n = 37.2$ cm^{-3}, $T = 64.5$ K) stable phases. For our choice of parameters, the cooling and sound crossing times in the unstable gas are equal at a scale $\lambda_{\rm eq} \sim 4$ pc. For the warm medium in thermal equilibrium, this scale increases to ~ 23 pc. The scale $\lambda_{\rm eq}$ also applies for equality of the turbulent crossing time and the cooling time for Mach-1 motions. Below this scale, classical isobaric perturbations would evolve nearly isobarically, because condensation occurs on roughly the cooling time, which is longer than the time needed to restore pressure balance (the sound crossing time). However, velocity perturbations below this scale generate perturbations that approach adiabatic behavior as their Mach number increases, because in this case the externally-applied turbulent compression exerts PdV work on the fluid parcel, heating it on timescales shorter than the cooling time.

In figure 1 we show a summary of the effective equation of state of the various simulations, characterized by the effective polytropic index $\gamma_{\rm e}$. This is the slope of the distribution of points in the pressure-density diagram (not shown), as a function of M and $k_{\rm for}$ for each run. The value of $\gamma_{\rm e}$ for each run is indicated by a point (+). As either M or $k_{\rm for}$ is increased, a progressive increase of $\gamma_{\rm e}$ is observed. This behavior implies a *decrease* in the mean pressure of the diffuse gas, and an *increase* in the mean pressure of the dense gas. In particular, the fraction of zones with densities $n > 7.1$ cm^{-3} and with $P > 10^4$ K cm^{-3} (fig. 2) increases from roughly 0.1% at $k_{\rm for} = 2$ (a driving scale of 50 pc) and $M = 0.5$ to roughly 70% for $k_{\rm for} = 16$ (a driving scale of 6.25 pc) and $M = 1.25$. In particular, for $M = 0.5$ and $k_{\rm for} = 2$, this fraction is $\sim 0.1\%$, similar to the value reported by Jenkins (2004) from a survey of the fine-structure excitation of CI on the Galactic plane.

Our simulations also indicate that the value of $\gamma_{\rm e}$ plays an important role in the determination of the pressure histogram shape. This is illustrated in figures 3 and 4, where it can be seen that the total pressure histogram widens as the Mach number is increased, and moreover develops near-power-law tails

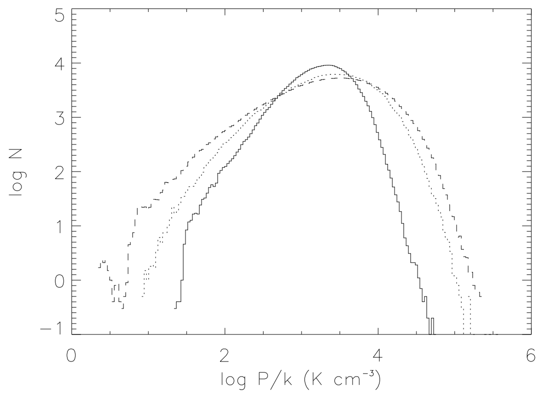

Fig. 4. Total pressure histograms for simulations with $k_{\rm for} = 16$ at $M \sim 0.5$ (*solid line*), $M \sim 1.0$ (*dotted line*), and $M \sim 1.25$ (*dashed line*).

at high (resp. low) pressures when $\gamma_{\rm e} \lesssim 0.5$ (resp. $\gamma_{\rm e} \gtrsim 1$), which occurs at $k_{\rm for} = 2$ (resp. $k_{\rm for} = 16$) in our simulations. The opposite side of the pressure histogram decays rapidly, in an approximately lognormal form. These results show that turbulent advection alone can generate large thermal pressure scatters, with power-law high-P tails for large-scale driving, and provide validation for approaches attempting to derive the shape of the pressure histogram through a change of variable from the known form of the density histogram, such as that performed by Mac Low et al. (2005).

The results we have shown can be understood simply as a consequence of the turbulent crossing time becoming shorter in local compressions as either the Mach number M or the driving wavenumber $k_{\rm for}$ are increased, creating a larger fraction of compressions that evolve closer to adiabatically, and thus temporarily drift away from thermal equilibrium.

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