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TURBULENT DISSIPATION IN THE INTERSTELLAR MEDIUM: IMPLICATIONS FOR GALAXY FORMATION AND EVOLUTION

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RESUMEN

Estudiamos la disipación turbulenta en el MIE y algunas implicaciones para la formación y evolución de galaxias usando simulaciones MHD numéricas de fluidos compresibles en 2D. La energía cinética E_k se inyecta por fuentes estelares formadas autoconsistentemente. En el fluido coexisten el régimen de turbulencia forzada y el de decaimiento. En las regiones turbulentas activas, E_k es disipada local y eficientemente. En el régimen de decaimiento $E_k(t)$ decae $\sim (1+t)^{-0.8}$. Los movimientos turbulentos residuales pueden propagarse distancias del orden del alto del disco gaseoso lo cual sugiere que la turbulencia puede propiciar el soporte vertical con una formación estelar autoregulada al nivel del disco, mas no al nivel de todo el halo cosmológico como se requiere en ciertos modelos de formación de galaxias.

ABSTRACT

We study turbulent dissipation in the ISM and explore some implications for galaxy formation and evolution using 2D MHD numerical simulations of compressible fluids. The turbulent kinetic energy E_k is injected by stellar sources formed self-consistently in the simulation. In the ISM-like fluid, regimes of both forced and decaying turbulence coexist. In the active turbulent regions (forced regime), E_k is dissipated locally and efficiently. In the decaying regime (far from input sources), $E_k(t)$ decays $\sim (1+t)^{-0.8}$. The residual turbulent motions may propagate distances of the order of the disk height, suggesting that turbulence may be responsible for vertical support and star formation self-regulation at the disk level, but not at the level of the whole cosmological halo, as would be required in some models of galaxy formation.

Key Words: **GALAXIES: EVOLUTION — GALAXIES: ISM — ISM: GENERAL — MHD — TURBULENCE**

1. INTRODUCTION

Modeling galaxy formation and evolution requires a solid cosmological theoretical framework as much as an adequate model to describe the large-scale star formation (SF) cycle and its interplay with the interstellar medium (ISM). The dissipative properties of the ISM play a crucial role in this latter process. Globally, stellar radiation is mainly responsible for maintaining the temperature of the ISM in its various phases. However, thermal pressure is thought to be negligible for the global disk gas dynamics (e.g., Vázquez-Semadeni et al. 2000; Cox, these proceedings). Nevertheless, stars are also sources of kinetic energy (E_k) deposition into the ISM, and as hydrodynamical simulations have shown, the dynamics of the gas in this case is deeply affected (e.g., Navarro & White 1993). Due to the large E_k input and the high Reynolds number of the ISM plasma, turbulence is expected to develop, its pressure and dissipation being key ingredients in the “metabolism” of the disk stellar-gas system.

Several disk galaxy evolution models (e.g., Firmani, Hernández, & Gallagher 1996) are based on the idea that the intrinsic SF rate (SFR) is controlled by a balance within the vertical *disk* gas between the turbulent energy input rate due to SF and the dissipation rate. The crucial parameter for the SFR and disk height is the turbulent dissipation timescale.

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The self-regulating SF mechanism has also been used in models of galaxy formation within the context of the hierarchical CDM-based scenario, but in this case it was applied to the large cosmological halo (White & Frenk 1991; Kauffmann, White, & Guiderdoni 1993; Cole et al. 1994; Somerville & Primack 1999; van den Bosch 1999). In these models the feedback of the stars is assumed to efficiently reheat and drive back the disk gas into the dark matter halo, in such a way that the SFR efficiency is a strong function of the halo mass. Thus, a crucial question is whether the energy released by SNe and stars is able to not only maintain the warm and hot phases and the stirring of the ISM, but also to sustain a huge hot corona in quasi-hydrostatic equilibrium with the cosmological halo.

It should be emphasized that the observed medium around the disks—diffuse ionized and high-velocity-dispersion HI gas, usually called the halo—is much more local than the hypothetical gas in virial equilibrium with the huge dark halo. We shall refer to the former as the the *extraplanar medium*, and to the latter as the *intrahalo medium*. It is still not at all clear how to explain the observed extraplanar medium, particularly the ionized gas (see a recent review by Mac Low 1999b). This calls into question the possibility that ionizing sources from the disk (mainly massive OB stars) are able to sustain the extended intrahalo medium. A possibility is that this gas is heated by turbulence from the disk. However, this question again depends on the ability of the turbulent ISM to dissipate its E_k. Avila-Reese & Vázquez-Semadeni (in preparation; hereafter AV) have studied the dissipative properties of compressible MHD fluids that resemble the ISM. Here we briefly report their main results and remark on the implications of the aforementioned questions.

2. THE METHOD

AV have used numerical 2D MHD simulations of self-gravitating turbulent compressible fluids that include terms for radiative cooling, heating, rotation and stellar energy injection (Vázquez-Semadeni, Passot, & Pouquet 1995, 1996; Passot, Vázquez-Semadeni, & Pouquet 1995). The parameters were chosen in such a way the simulations resemble the ISM in the plane of the Galaxy at the 1 kpc scale.

Previous simulations of dissipation in compressible MHD fluids were focused on studying molecular clouds (Mac Low, Klessen, & Burkert 1998; Stone, Ostriker, & Gammie 1998; Padoan & Nordlund 1999; Mac Low 1999a). In those works where the forced case was studied, the turbulence was driven in Fourier space by large-scale random velocity perturbations whose amplitudes were selected so as to maintain E_k constant in time. As a result, E_k is injected everywhere in space (a "ubiquitous" injection). Instead, in the ISM the stellar input sources are pointlike and their spheres of direct influence are comparatively small with respect to typical scales of the global ISM. In the simulations of AV, an "energy input source" is turned on at grid point $\vec{x}$ whenever $\rho(\vec{x}) > \rho_c$, and $\vec{\nabla} \cdot \vec{u}(\vec{x}) < 0$. Once SF has turned on at a given grid point, it stays on for a time interval Δt_s, during which the gas receives an acceleration $\vec{a}$ directed radially away from this point. The input sources are spatially extended by convolving their spatial distribution with a Gaussian of width λ_f. For the turbulent fluid, λ_f is the forcing scale. At this scale the acceleration $\vec{a}$ produces a velocity difference around the "star" $v_f \approx 2\vec{a}\Delta t_s$ (the velocity at which turbulence is forced at the λ_f scale). Both λ_f and v_f are free parameters.

3. DISSIPATION IN DRIVEN AND DECAYING REGIMES

For ISM simulations (128^2) with driven turbulence, AV find that the behaviour with time of the E_k dissipation rate, E_k^d, is similar to that of the E_k injection rate, $\dot{E}_k$. This means that E_k is dissipated locally, near the input sources. For various simulations varying λ_f and v_f, it was found that the dissipation timescale is given by

$$t_d \simeq 1.5 - 3.0 \times 10^7 \left(\frac{\lambda_f/30 \text{ pc}}{v_f/30 \text{ km s}^{-1}} \right) , \tag{1}$$

that is, t_d is proportional to λ_f/v_f.

Due to the locality and discreteness of the energy input sources, most of the volume is actually occupied by a turbulent flow in a decaying regime. Thus, one may say that in the same fluid "active" turbulent regions, where the turbulence is driven by small non-ubiquitous input sources is *locally* dissipated, coexist with extended regions of "residual" turbulence in a decaying regime and characterized by $v_{\rm rms}$, where $v_{\rm rms} \ll v_f$. In order to study the decaying regime, SF was turned off in the simulations after some time $t \gg t_d$. It was found that E_k decays as $(1+t)^{-n}$ with $n \sim 0.8$, in good agreement with previous studies for isothermal fluids (Mac Low et al. 1998; Stone et al. 1998). A typical decaying timescale, $t_{\rm dec}$, may be defined as the time at which the initial E_k has decreased by a factor 2. From our simulations, $t_{\rm dec} \approx 1.7 \times 10^7$ years, which is in agreement with t_d in the driven turbulence. With these timescales, "residual" turbulent motions propagating at roughly 10 km s^{-1} would attain typical distances of approximately 200 pc. It was also suggested, from dimensional arguments, that E_k and $v_{\rm rms}$ will decay with distance ℓ as ℓ^{-2m} and ℓ^{-m}, respectively, with $m = n/(2-n)$.

4. CONCLUSIONS AND IMPLICATIONS

• Localized, discrete forcing at small scales gives rise to the coexistence of both forced and decaying turbulence regimes in the same flow (ISM).

• The turbulent E_k near the "active" turbulent regions is dissipated locally and efficiently. The global dissipation timescale t_d is proportional to λ_f/v_f. For reasonable values of λ_f and v_f (which produce $v_{\rm rms} \sim$ 10 km s^{-1}), t_d is of the order of a few times 10^7 years. Far from the sources, the "residual" ISM turbulence decays as $E_k(t) \propto (1+t)^{-0.8}$. The characteristic decay time is again a few times 10^7 years, and for $v_{\rm rms} \sim 10$ km s^{-1}, the turbulent motions reach distances of ~ 200 pc.

• Turbulent motions produced in the disk plane will propagate up to distances of the order of the gaseous disk height. Therefore, models of galaxy evolution where this height is determined by an energy balance that self-regulates SF in the ISM appear viable. However, our results pose a serious difficulty for models of galaxy formation where the turbulent E_k injected by SNe is thought to be able to reheat and drive back the gas from the disk into the intrahalo medium in such a way that the SF is self-regulated at the level of the cosmological halo. Nevertheless, for non-stationary runaway SF (starbursts), most of the superbubbles might be able to blowout of the disk, as required for expelling large amounts of gas and energy into the dark matter halo.

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