Interstellar Turbulence Driving by Galactic Spiral Shocks

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ABSTRACT

Spiral shocks are potentially a major source of turbulence in the interstellar medium. To address this problem quantitatively, we use numerical simulations to investigate gas flow across spiral arms in vertically stratified, self-gravitating, magnetized models of galactic disks. Our models are isothermal, quasi-axisymmetric, and local in the quasi-radial direction while global in the vertical direction. We find that a stellar spiral potential perturbation promptly induces a spiral shock in the gas flow. For vertically stratified gas disks, the shock front in the radial-vertical plane is in general curved, and never achieves a steady state. This behavior is in sharp contrast to spiral shocks in two-dimensional (thin) disks, which are generally stationary. The non-steady motions in our models include large-amplitude quasi-radial flapping of the shock front. This flapping feeds random gas motions on the scale of the vertical disk thickness, which then cascades to smaller scales. The induced gas velocity dispersion in quasi-steady state exceeds the sonic value for a range of shock strengths, suggesting that spiral shocks are indeed an important generator of turbulence in disk galaxies.

INTRODUCTION

- Supersonic turbulence is subject to fast decay in the absence of driving (e.g., Ballesteros-Paredes et al. 2006).
  - ➢ Question: What are the driving mechanisms?
  - ➢ Candidates: HII region expansion, supernova explosions, and fluid instabilities (MRI, GI, TI), etc (see Mac Low & Klessen 2004; Elmegreen & Scalo 2004 for recent reviews).
- Galactic rotation also has a large amount of kinetic energy.
  - ➢ Question: How to convert a rotational energy to a random turbulent energy?
  - ➢ Candidates: Galactic spiral shocks or fluid instabilities involving rotation.
- Previous studies involving galactic spiral shocks include 2D models in a galactic plane (e.g., Woodward 1976; Wada & Koda 2004; Bonnell et al. 2006) or 3D models with a poor vertical resolution (e.g., Tubbs 1980). Recent simulations show that spiral shocks in a vertically stratified disk develop significant nonsteady motions (e.g., Martos & Cox 1998; Gomez & Cox 2002, 2004; Boley & Durisen 2006; Kim & Ostriker 2006).
  - ➢ Question: Can galactic spiral shocks be a substantial source of turbulence in spiral galaxies?
  - ➢ Answer of this work: YES!

BASIC EQUATIONS

- We solve isothermal MHD equations in a local regions of self-gravitating, differentially rotating, magnetized galactic gaseous disks.

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{V}_T)=0$$

$$\frac{\partial\mathbf{V}}{\partial t}+\mathbf{V}_T\cdot\nabla\mathbf{V}=-\frac{1}{\rho}\nabla P+\frac{1}{4\pi\rho}(\nabla\times\mathbf{B})\times\mathbf{B}+q_0\Omega_0V_x\hat{\mathbf{y}}-2\mathbf{\Omega}_0\times\mathbf{V}-\nabla(\Phi_s+\Phi_{ext})$$

$$\frac{\partial\mathbf{B}}{\partial t}=\nabla\times(\mathbf{V}_T\times\mathbf{B})$$

$$\nabla^2\Phi_s=4\pi G\rho$$

$$P=c_s^2\rho$$

- Initial velocity due to galactic rotation.

$$\mathbf{V}_0=R_0(\Omega_0-\Omega_p)\sin i\hat{\mathbf{x}}+[R_0(\Omega_0-\Omega_p)-q_0\Omega_0x]\hat{\mathbf{y}}$$

- We adopt a linear vertical gravity and a sinusoidal spiral potential.

$$\Phi_{ext}=\left(\frac{\pi G\Sigma_*}{\sigma_{*,z}}\right)^2z^2+\Phi_{sp}\cos\left(\frac{2\pi x}{L_x}\right)$$

- Our models are quasi-axisymmetric. $\frac{\partial}{\partial y}\rightarrow 0$

NUMERICAL METHODS

- Scheme:
  - ✓ 2.5D ZEUS code (Stone & Norman 1992a,b)
- Boundary conditions:
  - ✓ Sheared-periodic boundary conditions in x
  - ✓ Reflection symmetry w.r.t. the midplane
  - ✓ Open boundary conditions at $z=L_z=4H$
- Velocity decomposition for advection. $\mathbf{V}=\mathbf{V}_T-\mathbf{V}_0$

MODEL PARAMETERS

- Three KEY parameters

$$Q_0=\frac{\kappa_0c_s}{\pi G\Sigma_0}\qquad\beta_0=\frac{c_0^2}{\mathrm{v}_A^2}\qquad F=\frac{2}{\sin i}\frac{|\Phi_{sp}|}{R_0^2\Omega_0^2}$$

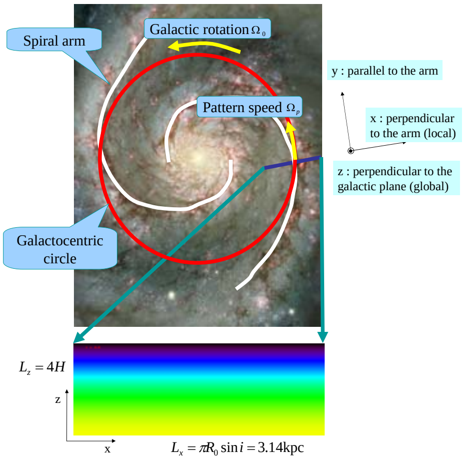
- Effective isothermal sound speed $c_s=7\,\mathrm{km\,s^{-1}}$
- In the solar neighborhood,

$$R_0=10\,\mathrm{kpc},\ \Omega_0=26\,\mathrm{km\,s^{-1}\,kpc^{-1}},\ \kappa_0=\sqrt{2}\Omega_0.$$

- For the spiral arm parameters,

$$\Omega_p=0.5\Omega_0,\ \sin i=0.1$$

COORDINATES



MODELS AND RESULTS

	Q	β	F	Res.	H(pc)	$\langle\sigma_x^2\rangle^{1/2}/c_s$	$\langle\sigma_y^2\rangle^{1/2}/c_s$	$\langle\sigma_z^2\rangle^{1/2}/c_s$	M_{eff}
A	1.8	Inf.	5%	1024^2	196	0.66	0.63	0.38	4.0
B	1.8	Inf.	5%	512^2	196	0.67	0.62	0.36	3.9
C	2.0	Inf.	7%	512^2	218	1.01	0.86	0.45	5.0
D	2.5	Inf.	10%	512^2	272	1.55	1.20	0.58	6.2
E	1.5	10.	5%	512^2	169	0.64	0.52	0.31	3.8
F	1.8	10.	7%	512^2	203	0.93	0.79	0.42	4.4
G	2.0	10.	10%	512^2	225	1.54	1.19	0.52	5.4

- Density-weighted velocity dispersions.

$$\sigma_i^2=\frac{\int\rho\delta V_i^2dxdz}{\int\rho dxdz},\ \delta V_i=V_i-\langle V_i\rangle$$

time average over t/t$_{orb}$~4-8

- Effective Mach number from one-dimensional counterparts → characterizes the shock strength.

$$M_{eff}=\langle\Sigma_{post}/\Sigma_{pre}\rangle^{1/2}$$

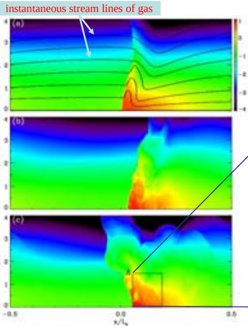


FIGURE 1: Snapshots of density in logarithmic color scale of model G at t/t$_{orb}$ = 1.2, 1.7, 1.8 from top to bottom.

NONSTEADY MOTIONS

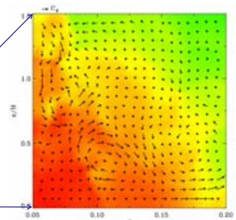


FIGURE 2: Velocity vectors and density in logarithmic scale at t/t$_{orb}$ = 3.2 in the region A marked in Fig. 1c.

- Our model simulations show that spiral shocks in the XZ plane never achieve a steady state (Figure 1).
  - ✓ When the vertical gravity exceeds the vertical repulsive pressure force, the shock front at high |z| bends downstream (Figure 1b).
  - ✓ As gas is further compressed, vertical pressure gradients overwhelm vertical gravity, and the gas near midplane is able to rebound to high |z|, and the shock front at high |z| shifts back upstream (Figure 1c).
  - ✓ The vertically rebounding gas overshoots equilibrium, vertical gravity again dominates, and the cycle repeats → flapping motions
- The small-scale vortical motions are appeared at postshock regions that aid in transfer of random gaseous kinetic energy to smaller scale (Figure 2).

LEVEL OF ISM TURBULENCE

- Random gas motions in model G are supersonic in the x- and y-directions, and exhibit large-amplitude temporal fluctuations (Figure 3a).
- Evidently, the system reaches a quasi-steady state in which dissipation of turbulence (in shocks and trough cascades) is offset by the continual input of new turbulent energy from the large-scale flapping.

- For $M_{eff}<5.5$, σ_{tot} monotonically increases roughly as $\sigma_{tot}/c_s=0.6M_{eff}-1.4$
- For $M_{eff}>5.5$, σ_{tot} is more or less constant at about $\sigma_{tot}=2c_s$

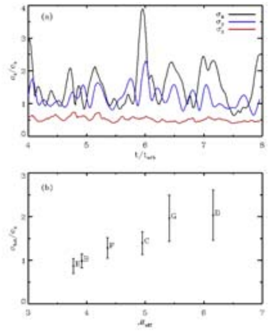


FIGURE 3: (a) Time evolution of the density-weighted velocity dispersions in model G. (b) Total velocity dispersion vs. the effective Mach number in models B-G.

DISCUSSION

- **The random gas motions induced by the spiral shock persist despite strong shock dissipation.**
- **The time-averaged in-plane velocity dispersions ~7-10 km/s for a range of shock strength which are similar to the observed line widths of atomic gas in the MW (e.g., Heiles & Troland 2003).**
- **Vertical velocity dispersions are lower, but still amount to ~0.5c$_s$.**
- **Radio observations of extended H I disks in face-on galaxies show that the total vertical velocity dispersions are as large in the outer parts as in the inner regions (van Zee & Bryant 1999), suggesting that additional sources (such as MRI) of turbulence are able to compensate when needed.**
- **While in this work we adopt isothermal conditions for the gas and take the mean magnetic field parallel to the spiral arm, the real ISM has a multiphase structure and is threaded also by weak vertical magnetic fields (Piontek & Ostriker 2004, 2005).**