The Biggest Accretion Disks
Turbulence and Structure in the Diffuse ISM

Eve Ostriker & Rob Pontek
University of Maryland

OUTLINE

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I. Introduction

Orientation: global properties of the ISM in spiral galaxies

- Surface density: $\Sigma_{\text{tot}} = \text{few} \cdot 100 \, M_\odot \, \text{pc}^{-2}$
  - $\Sigma_{\text{H}_2} \leq 10 \, M_\odot \, \text{pc}^{-2}$
  - Balance $\Sigma_{\text{H}_2}$

- Distribution:
  - $\text{H}_2$ is preferentially in arms: in grav. bound GMCs
  - HI diffuse: non-SG clouds

- Scale height (MW; atomic):
  - $H = 150 \, \text{pc}$ inner ($R < 8 \, \text{kpc}$)
  - outer up to $500 \, \text{pc}$

- Midplane density (MW; inner galaxy):
  - $n_{\text{H}_2} = 0.6 \, \text{cm}^{-3}$
  - outer ($R > 14 \, \text{kpc}$)

- $f_\text{M} < 0.6$ cm$^{-3}$
ISM structure

- Large scale
  - Concentration in spiral arms; due to external potential and SG

- Medium scale
  - Spurs trailing from arms into interarm regions
  - Superclouds \((M \sim 10^7 M_\odot)\) of \(H_2 + HI\) in arms
  - Bubbles and chimneys of hot gas

- Small scale
  - \(H_2\) GMCs \((M = 10^5 - 10^6 M_\odot)\), and dark clouds \((M < 10^4 M_\odot)\);
    \((n \sim 100 \text{ cm}^{-3}, n \text{ to } 10^5 \text{ cm}^{-3}; T \sim 10K; L \sim 20 - 50 \text{ pc})\)
  - Cold atomic clouds \((n \sim 30 \text{ cm}^{-3}, T \sim 100K, L \sim 1 - 10 \text{ pc})\)
  - Diffuse warm, atomic gas \((n \sim 0.3; T \sim 10^4K) + \text{WIM and HIM (}T = 10^5 - 10^6 K)\) surrounds clouds

ISM turbulence

- Milky Way:
  - Turbulent \(\delta v \sim 7 \text{ km s}^{-1}\) for both warm, cold HI gas near Sun (Heiles & Troland 2003)
  - WIM \(\delta v \sim 10 - 30 \text{ km s}^{-1}\) (Tufte, Reynolds, & Haffner 1999)

- External galaxies:
  - Measured for face-on galaxies; total HI \(\delta v \sim 6 - 12 \text{ km s}^{-1}\)
  - No secular trend of \(\delta v\) with galactic radius, even outside optical disk
  - Variations in \(\delta v\) uncorrelated with spiral arm phase/star formation

NGC 1058 -- Dickey et al 1990; Petric & Rupen 2001
NGC 1232 -- van Zee & Bryant 1999

Heiles & Troland (2003)
Magnetic Fields

Observations/diagnostics

- MW clouds:
  - Zeeman effect $\langle B_\parallel \rangle$
  - Polarized stellar extinction $\langle B_\perp \rangle$ dir.
  - Polarized far-IR/sub-mm em.$\langle B_\perp \rangle$

- MW diffuse ionized gas:
  - pulsar Faraday rotation $\langle B_\parallel \rangle$

- MW & external galaxies
  - synchrotron emission $\rightarrow B_{\text{sync}}$
  - polarized synchrotron $\rightarrow \langle B_\perp \rangle$

⇒ Galactic-scale results consistent with
  - mainly-toroidal ordered field,
  - comparable "random" field
  - total field $\sim 5 - 15 \mu$G
  - Magnetic energy densities comparable to thermal, turbulent kinetic

(Beck 1999, 2001)

Neininger (1992)
II. Turbulence Issues

``Astrophysics” questions

• What generates turbulent $v$, $B$?
• How does turbulence affect physical structure? e.g.
  – Cloud mass spectrum?
  – Vertical distribution of gas?
  – Density profiles across spiral arms?
• How does physical structure affect turbulence? e.g.
  – Effect of cloudy/multiphase structure on turbulent driving and dissipation?
  – Effect of cloudy structure on turbulent power spectrum?
• How are turbulence and thermal ISM properties related?
  – Is turbulent heating/cooling important?
"Astronomy" issues

- *How do turbulence & structure in the ISM affect star formation?*
- Star formation takes place in massive GMCs, likely formed via gravitational instabilities
  - How do GMC formation rates depend on ISM turbulence?
  - How do cloud properties (masses, internal turbulent states, etc.) depend on diffuse ISM turbulence?
  - How is the galactic GMC distribution affected by turbulence & structure in the diffuse ISM?

Turbulent driving

- Traditional view: driving by supernovae (cf. Spitzer)
  - \((dE_{\text{turb}}/dt)_{\text{in}} = \varepsilon_{\text{SN}} \varepsilon_{\text{SF}} E_{\text{SN}}/(m_{\text{SN}} t_{\text{cloud form}})\)
  - \((dE_{\text{turb}}/dt)_{\text{out}} \sim (\delta v)^2/t_{\text{cloud collis}} \sim (\delta v)^3/H\)
  - Using \(t_{\text{cloud form}} \sim t_{\text{torb}} = 2.5 \times 10^8 \text{ yrs}\), \(t_{\text{cloud collis}} \sim H/\delta v\) with \(H=150 \text{ pc}\),
    \(\varepsilon_{\text{SF}} \sim 0.1\), \(\varepsilon_{\text{SN}} \sim \delta v/(4v_{\text{SN,cool}})\) with \(v_{\text{SN,cool}} \sim 85 \text{ km s}^{-1}\), \(m_{\text{SN}} \sim 250 M_{\odot}\),
    this yields
    \(
    \delta v \sim 6 \text{ km s}^{-1}
    \)
    consistent with observations, but is it a coincidence??
- Problems with SN driving
  - Intermittency of SF
  - No observed correlation of turbulence with SF
  - Outer disks lack SF but are (likely) turbulent
- Another potential source of turbulence: tap galactic rotation with MRI (cf. Sellwood & Balbus 1999)
  - Principal difference from MRI in previous (accretion disk) models is that ISM gas is cloudy/multi-phase
III. Galactic MRI models

Numerics / model specifications

- Time-dependent integration of MHD variables using version of ZEUS code (Stone & Norman 1992a,b)
- Simple atomic cooling+diffuse heating fit (cf Wolfire et al 2003); energy update via implicit solver
- Conduction implemented to spatially resolve thermally-unstable wavelengths on computational grid
- Local Cartesian model with shearing-periodic boundary conditions (Hawley, Gammie, & Balbus 1995; Stone et al 1996)
- 2D poloidal-plane “XZ” models in (100pc)$^2$ box (Piontek & Ostriker 2004)
- 3D models in (200pc)$^3$ box (Piontek & Ostriker 2005a)
- 3D stratified models in 600pcX300pcX900pc box (Piontek & Ostriker 2005b)
- Initial $P_0/k=2000$ K cm$^{-3}$; initial $n=0.25$-4 cm$^{-3}$; initial $\beta=100$
Shearing periodic box

For local models, consider a small patch of the disk, neglecting the curvature of the coordinates.

Interior rotation is faster for “normal” outer-disk shear.

Exterior rotation is slower for “normal” shear.

To gal.ctr.

Shearing-periodic boundary conditions

Magnetohydrodynamic equations in the local frame

- Continuity equation:
  \[
  \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
  \]

- Momentum equation:
  \[
  \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = - \frac{\nabla P}{\rho} + \frac{\nabla \times (\mathbf{v} \times \mathbf{B}) \times \mathbf{B}}{4\pi \rho} + 2q \Omega^2 \mathbf{x} - 2\Omega \times \mathbf{v} - \nabla \Phi_s + \mathbf{g}_{\text{ext}}
  \]

  Dimensionless shear parameter \( q = -\text{dln}\Omega/\text{dln}R \);

  epicyclic frequency \( \kappa^2 = 2(2-q)\Omega^2 \); background \( \mathbf{v}_0 = -q \Omega \mathbf{x} \)

- Energy equation:
  \[
  \frac{\partial \mathcal{E}}{\partial t} + \mathbf{v} \cdot \nabla \mathcal{E} = -(\mathcal{E} + P) \nabla \cdot \mathbf{v} - \rho(\mathbf{v} \cdot \nabla \mathbf{v}) - \nabla \cdot (\mathbf{K} \nabla T)
  \]

- Induction equation:
  \[
  \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})
  \]

- Poisson equation:
  \[
  \nabla^2 \Phi_s = 4\pi G \rho
  \]
Thermal Instability and HI structure

- Thermal instability develops due to bistable heating/cooling equilibrium curve
- Medium becomes segregated into cold clouds/warm intercloud gas within ~20 Myr
- TI produces turbulence, but amplitude is very low (<0.4 km s\(^{-1}\))

Growth of MRI in cloudy medium

- Growth rates ~ same as in single-phase medium at same \(\bar{\rho}\), provided intercloud separation < \(\lambda/2\)
- Clouds grow by agglomeration; strong bends in B-field are in clouds
- Channel flow dominates late stages of 2D models
Development of 3D saturated-state turbulence

- $256^3$ box
- $(200\text{pc})^3$
- $t_{\text{max}} = 9$ orbits
  $= 2.3 \times 10^9 \text{ yrs}$

Turbulence history

- Standard model: initial $\langle n \rangle = 1 \text{ cm}^{-3}$; $\langle B_z \rangle = 0.26 \mu \text{G}$
- Late time: $\delta v_{\text{tot}} = 2.7 \text{ km s}^{-1}$; $\delta v_x = 1.9$, $\delta v_y = 1.7$, $\delta v_z = 0.7 \text{ km s}^{-1}$
  \[ B_{\text{tot}} = 2-3 \mu \text{G}; \quad B_x = 1.3, \quad B_y = 1.9, \quad B_z = 0.5 \mu \text{G}; \]
  similar values in all phases
- Compare with isothermal model with same $\langle B_z \rangle$, $\langle n \rangle$, $P_{\text{late}}$:
  $\delta v_{\text{tot}} = 4 \text{ km s}^{-1}$; $B_{\text{tot}} = 3.5 \mu \text{G}$

velocity

magnetic field
Scalings of saturated-state turbulent stresses

- Vary mean density in the box; other parameters fixed
- $\left\langle B_x B_y \right\rangle P_0 \propto \left(\n_0 n\right)^{0.4}$
- $\left(\rho v_x v_y \right) P_0 \propto \left(\n_0 n\right)^{1.1}$
- $L \propto \Omega \Delta \propto \left(\n_0 n\right)^{0.5}$
- $A \propto \Delta \propto \left(\n_0 n\right)^{0.75}$

HGB(95) stresses $\propto n_0^{0.4} \propto \left(\n_0 n\right)^{0.5}$
Sano et al (2004) stresses $\propto \left(\n_0 n\right)^{0.75}$

Saturation scalings of $\delta v$

- $(\delta v)^{2/2} \propto \left(\n_0 n\right)^{-0.77}$ (or $\left(\n_0 n\right)^{-0.7}$ for warm-only)
- this agrees with scaling prediction from equating
  $dE/dt_{\text{MRI input}} \sim \Omega \Delta \propto \left(\n_0 n\right)^{1.4}$
  with
  $dE/dt_{\text{dissipation}} \sim (\delta v)^{3/2} \propto \left(\n_0 n\right)^{0.77}$
- At low $\n_0$, cold cloudlets are trans-sonic with respect to warm medium (up to 8 km s$^{-1}$)
- Low-$\n_0$ velocity dispersions are large enough to provide large outer-galaxy turbulence

Maxwell stress

Reynolds stress

Mach number
Saturation scalings of $B^2$

- $\langle B^2 \rangle$ independent of $\langle n \rangle$, unlike single-phase results
- set by ambient pressure ($B_{\text{sat}} \sim 1$)?
- role of physical densities?

B-field strength

Thermal structure with turbulence

- Pressure, temperature ($\rho$, $k$, $T$) broad with turbulence
- Not "phase continuum", quasi-two-phase state persists, since $t_{\text{cool}} < t_{\text{turb diss}}$

Temperature

Pressure
Energetics

- ~1/4 of MRI input energy is captured (in shock heating)
- PdV work provides net cooling (expansion), 30% of shock heating
- Radiative processes provide net cooling, 70% of shock heating

\[ \varepsilon_{th}/(dE/dt)_{MRI} = 60 \text{Myr} \]
\[ \varepsilon_{th}/(dE/dt)_{shocks} = 100 \text{Myr} \]

Compare to:
\[ t_{cool} \sim \text{few Myr in warm/diffuse gas;} \]
\[ t_{cool} \sim \text{few } 10^4 \text{yr in cold/dense gas} \]

Total mass fractions

- Mass fraction in cold component increases with \( \langle n \rangle \); exceeds static prediction at low \( \langle n \rangle \) due to turbulent compression
- Thermally-unstable and warm components have comparable mass at all \( \langle n \rangle \)
Spatial distribution of thermal phases

- Thermally-unstable gas is in envelopes surrounding cold gas

Cloud mass function

- Characteristic scale $M \sim 100 \, M_\odot \Rightarrow L \sim 7 \, \text{pc}$
- Consistent with equating $t_{\text{shear}} \sim t_{\text{collis}}$
IV. Turbulence and gravity

Multiphase gas + MRI + external g

3D stratified model development

- $256 \times 128 \times 384$ box
- $t_{\text{max}} = 10$ orbits
  
  $= 2.5 \times 10^9$ yrs
- $n_{\text{init}}(z=0) = 1 \, \text{cm}^{-3}$
- $H_{\text{init}} = 150 \, \text{pc}$
- $\Sigma_{\text{tot}} = 10 \, M_\odot \, \text{pc}^{-2}$
Vertical profile in saturated state

Comparison of turbulent and quiescent states

<table>
<thead>
<tr>
<th>State</th>
<th>Warm mass fraction</th>
<th>Warm scale height</th>
<th>Cold mass fraction</th>
<th>Cold scale height</th>
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<tr>
<td>quiescent</td>
<td>0.76</td>
<td>240pc</td>
<td>0.50</td>
<td>220pc</td>
</tr>
<tr>
<td>turbulent</td>
<td>0.24</td>
<td>7pc</td>
<td>0.25</td>
<td>70pc</td>
</tr>
</tbody>
</table>
Determining thresholds for gravitational instability

- To determine threshold for gravitational runaway, growth time, and cloud properties, require numerical simulations
  - 2D models show:
    - $Q_{crit} = 1.2 - 1.4$ for a range of $B$
    - $t_{CF} \sim 0.5 - 3 \ t_{\text{orb}} \sim 10^8 - 10^9$ yrs
    - $M_{\text{cloud}} \sim 0.5 - 7 \ M_j \sim 10^7 - 10^8 \ M_\odot$

Results from 3D simulations:

- Thresholds for nonlinear instability:
  - $Q_m < 1$ unmagnetized case
  - $Q_m \sim 1$ strongly magnetized case
  - $Q_m \sim 1.8$ for weakly magnetized cases (MRI unstable)
- Growth takes few-several $t_{\text{orb}} \sim 10^8 - 10^9$ yrs
- Characteristic $M \sim M_j \sim 10^7 \ M_\odot$

MRI decreases surface density required for gravitational instability by >50%

Unmagnetized model: $Q=0.7$

Weakly-magnetized (MRI) model: $Q=1.5, \beta_0=100$

Further issues for GMC formation models....

- How do cloud formation rate/critical $Q$ depend on turbulence in multiphase gas?
- What is appropriate weighting of $\sigma_{\text{turb}}$ ($\delta \nu$ and $\delta v_A$) and $\sigma_{\text{therm}}$ in $c_{\text{eff}}$ for $L_j = c_{\text{eff}}^2/(G\Sigma)$ and $t_j = c_{\text{eff}}/(G\Sigma)$ in multiphase gas?
- Do star-forming clouds preferentially develop from thermally- and/or dynamically-cold components?
- Is MRI-driven turbulence crucial for shutting off star formation in the outer parts of disks?

...stay tuned!

Summary/open issues

- Galactic ISM is a BIG (spatially resolved!) accretion disk
- Special characteristic: multiphase, cloudy structure, due to cooling curve properties
- Galactic MRI:
  - grows in cloudy gas at comparable rate to single-phase MRI
  - has scalings with $\langle n \rangle$ of $\langle B B \rangle$, $\langle v_B \rangle$, and $\langle \delta \nu^2 \rangle$ in cloudy gas similar to single-phase models; however $\langle B^2 \rangle$ is $\langle n \rangle$-independent
  - result $\langle \delta \nu^2 \rangle \propto \langle n \rangle^{-0.77}$ is consistent with balance of MRI driving with cloud-collision dissipation
  - produces large $\langle \delta \nu^2 \rangle$ for $\langle n \rangle$ characteristic of outer galaxies' ISM
  - broadens, but does not eliminate, two-phase thermal structure
  - lends significant (turbulent) vertical support to lift cold gas off the midplane
  - in warm-dominated case, raises the Toomre $Q$ threshold for (nonaxisymmetric) GMC-forming gravitational instabilities by $>50\%$; effects in warm/cold medium TBD
- Questions:
  - What basic properties of a medium set the saturated-state amplitudes of MRI?
  - What other accretion disks may have two-phase structure, with what consequences? Are coronae mixed into the "thin" disk?