Turbulence and Structure in the Atomic Interstellar Medium

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OUTLINE

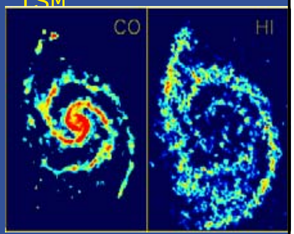
I. Introduction -- properties of the ISM in spiral galaxies
II. ISM turbulence: causes, effects, & issues
III. Galactic MRI models
IV. Summary & open questions

I. Introduction

Orientation: global properties of the ISM

- Surface density:
  - Σ_{tot} = few -100 $M_\odot$ pc^{-2} ;
  - Σ_{HI} $\leq$10 $M_\odot$ pc^{-2}
  - $\Sigma_{H2} \approx \Sigma_{tot} - \Sigma_{HI}$
- Scale height (MW; atomic):
  - H~150 pc inner (R< 8 kpc)
  - outer up to ~ 500pc
- Midplane density (MW; atomic):
  - n_{HI}=0.6 cm^{-3} inner galaxy; <0.3cm^{-3} outer (R>14 kpc)
- Other ISM components
  - warm ionized gas
  - hot gas

  f_M small; f_V up to ~0.5



M51 gas (Stuart Vogel/BIMA SONG)

Milky Way HI (Dickey & Lockman)

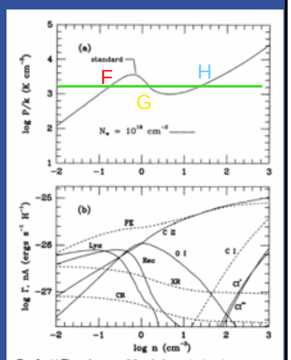
Warm/cold ISM structure

- Large scale structure
  - Concentration in spiral arms; due to stellar and gas gravity
- Medium scale structure
  - Spurs trailing from arms into interarm regions
  - Superclouds (M~10^7 $M_\odot$) of H_2+HI in arms
  - Walls surrounding bubbles and chimneys of hot gas
- Small scale structure
  - H_2 GMCs (M=10^5-10^6 $M_\odot$), and dark clouds (M<10^4 $M_\odot$):
    ④n⑤ ~100 cm^{-3};T~10K; L~20 - 50pc
    internal clumps, cores have n =10^3-10^5 cm^{-3}
  - Cold atomic clouds, sheets, & filaments
    n~30cm^{-3} , T~100K, L~1-10pc
    also tiny scale substructure within HI clouds
- "Unstructure": diffuse gas surrounding clouds
  Warm, atomic gas (n~0.3; T~10^4K)
  Also, warm and hot ionized gas (T=10^5-10^6K)

Atomic gas: equilibrium thermodynamics

- Thermal equilibrium at fixed pressure (Field, Goldsmith & Habing 1969):
  - warm (F), intermediate (G), cold (H)
  - Phases F and H are stable
  - Phase G is unstable
- In radiative and dynamical equilibrium,

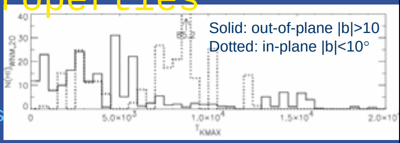
  T~200-5000 K gas would be thermally unstable ⇒ excluded



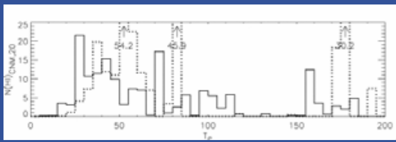
Wolfire et al (1995)

Atomic gas: thermal properties

- *High latitudes*: significant non-equilibrium intermediate-*T* gas is inferred from HI linewidths
- *Midplane:* more of gas is in stable-*T* range
- Cold gas: consistent with equilibrium



Warm gas temperature limits



Cold gas temperatures

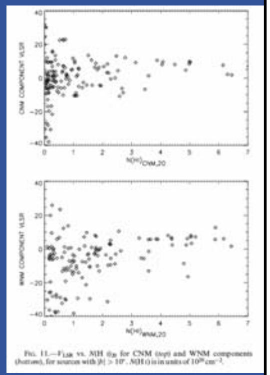
(Heiles & Troland (2003)

ISM turbulence

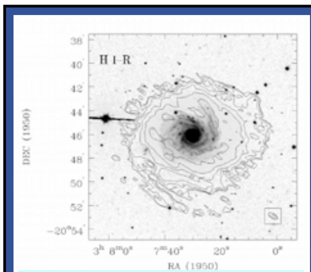
- Milky Way:
  - Turbulent $\delta v \sim 7$ km s^{-1} for both warm, cold HI gas near Sun (Heiles & Troland 2003)
  - Turbulent $\delta v \sim 1$ km s^{-1} $(R/pc)^{1/2}$ for molecular clouds (Solomon et al 1987)
  - WIM $\delta v \sim$ 10-30 km s^{-1} (Tufte, Reynolds, & Haffner 1999)
- External galaxies:
  - Measured for face-on galaxies; total HI $\delta v \sim$ 6-12 km s^{-1}
  - No secular trend of δv with galactic radius, even outside optical disk
  - Variations in δv uncorrelated with spiral arm phase/star formation

  NGC 1058 -- Dickey et al 1990; Petric & Rupen 2001

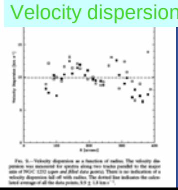
  NGC 1232 -- van Zee & Bryant 1999)



Heiles & Troland (2003)



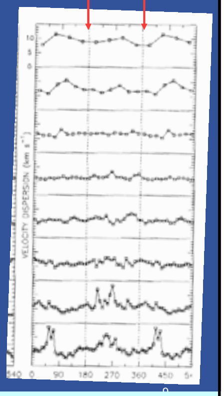
Velocity dispersion vs. R



NGC 1232 (van Zee & Bryant 1999)

increasing galactic radius

Spiral arm peak phase



NGC 1058 (Dickey, Hanson, & Helou 1990)

Velocity dispersion vs. ϕ

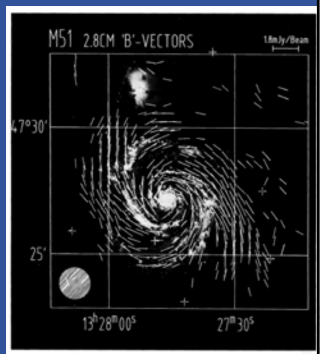
Magnetic Fields

Observations/diagnostics

- MW clouds:
  - Zeeman effect in HI, OH $\langle B_{\|} \rangle$
  - 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 $\langle B_{\|} \rangle$
- MW & external galaxies
  - synchrotron emission ⌫ $B_{tot,\perp}$
  - polarized synchrotron ⌫ $\langle B_{\perp} \rangle$

⇒ Galactic-scale results consistent with
- mainly-toroidal ordered field,
- comparable "random" field
- total field ~5 -15μG
- Magnetic energy densities comparable to thermal, turbulent kinetic (Beck 1999, 2001)
- MW local total field ~6 μG
- MW local vertical field ~0.3 μG

Heiles &Troland (2005); Han et al (1999)



Neininger (1992)

II. Turbulence Issues

Basic questions: atomic gas

- What generates turbulent *v, B* ?
- How does turbulence affect physical structure? e.g.
  - Cloud mass spectrum?
  - Vertical distribution of gas?
  - Profiles across spiral arms?
- How does physical structure affect turbulence? e.g.
  - Effect of 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? Can this explain out-of-equilibrium HI temperatures?

Related issues

- *How does turbulence in the atomic 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?
    - Do turbulent δv and δv_A contribute to support against self-gravity?
  - How do GMC properties (masses, internal turbulent states, rotation…) depend on diffuse ISM turbulence?

Turbulent driving

- Traditional view: driving by supernovae (cf. Spitzer)

  Per unit mass of the ISM,
  - $(dE_{turb}/dt)_{in} = \varepsilon_{SN} E_{SN} \varepsilon_{SF} /(m_{SN}\ t_{cloud\ form})$ SN rate
  - $(dE_{turb}/dt)_{out} \sim (\delta v)^2/t_{cloud\ collis}$

  Using $t_{cloud\ form} \sim t_{orb} = 2.5\times10^8$ yrs, $t_{cloud\ collis} \sim H/\delta v$ with H=150 pc, $\varepsilon_{SF} \sim 0.1$, $\varepsilon_{SN} \sim \delta v/(4 v_{SN,cool})$ with $v_{SN,cool} \sim 85$ kms^{-1}, $m_{SN} \sim 250\ M_\odot$, this yields

  $\delta v \sim 6$ kms^{-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, contain cold gas

Other potential non-stellar sources of ISM turbulence

- Spiral shocks in 3D are unstable; leads to turbulence on scale ~ disk thickness and below
- Self-gravity+shear+Coriolis swing-amplifies ~kpc-scale wavelets; turbulent energy cascades to smaller scales
- Tap galactic rotation with Magneto-Rotational Instability (cf. Sellwood & Balbus 1999)
  - MRI is driven by magnetic tension forces in rotating disk wherever Ω decreases outward
  - Difference from MRI in accretion disk models is that ISM gas is cloudy/multi-phase

Currently under study with Woong-Tae Kim

Contribute in regions where self-gravity is strong

Focus of today's talk

III. Galactic MRI models

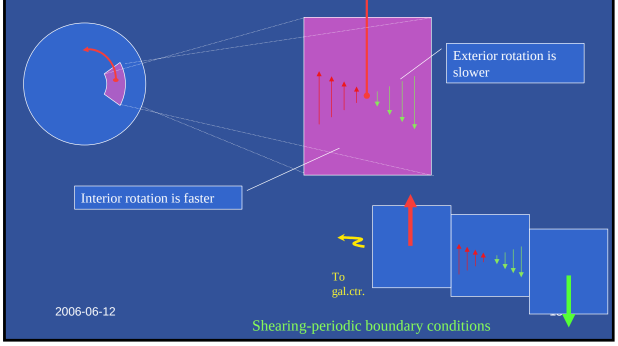
Numerics/model specifications

- Time-dependent integration of MHD variables using version of ZEUS code (Stone & Norman 1992a,b)
- Atomic cooling+diffuse heating fit (cf Wolfire et al 1995,2003);

  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 2005)
  - Initial n=0.25-4 cm^{-3} ; initial B_z=0.3μG
- 3D stratified models in 2H×2H×6H box with varying g_{ext} (Piontek & Ostriker 2006)
  - Initial B_z=0.3μG;
  - Inner disk models: initial $\Sigma_{tot}=10\ M_\odot\ pc^{-2}$; low, med., high g_{ext}
  - outer-disk mode: initial $\Sigma_{tot}=6\ M_\odot\ pc^{-2}$; low g_{ext}

Shearing periodic box

In local models, we are considering a small patch of the disk, neglecting the curvature of the coordinates



Shearing-periodic boundary conditions

Magnetohydrodynamic equations in the local frame

- Continuity equation: $\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \mathbf{v}) = 0$
- Momentum equation:

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v} = -\frac{\nabla P}{\rho} + \frac{(\nabla\times\mathbf{B})\times\mathbf{B}}{4\pi\rho} + 2q\Omega^2 \mathbf{x} - 2\Omega\times\mathbf{v} + \mathbf{g}_{ext}$$

Dimensionless shear parameter q=-dlnΩ/dlnR↗1;

epicyclic frequency $\kappa^2 = 2(2-q)\Omega^2$; background $v_0 = -q\Omega x\, \hat{y}$

- Energy equation:

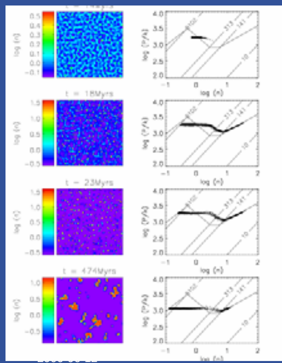
$$\frac{\partial \mathcal{E}}{\partial t} + \mathbf{v}\cdot\nabla\mathcal{E} = -(\mathcal{E}+P)\nabla\cdot\mathbf{v} - \rho(\rho\Lambda - \Gamma) + \nabla\cdot(K\ \nabla T)$$

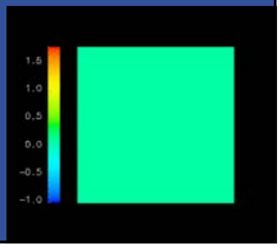
- Induction equation: $\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B})$

Thermal Instability and HI structure

- Thermal instability develops due to bistable heating/cooling curve
- Medium separates into cold clouds + warm intercloud gas in <20 Myr
- Overall cooling towards $P_{min,cold}$
- TI produces turbulence, but amplitude is very low (<0.4 kms^{-1})

(see also: Brandenburg et al 2006, Koyama & Inutsuka 2006)

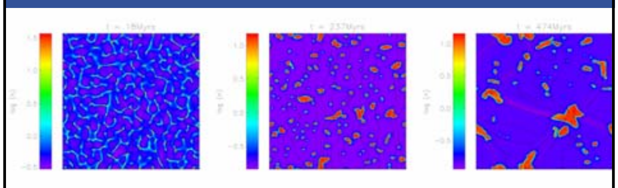




Piontek & Ostriker (2004)

Growth of MRI in cloudy medium

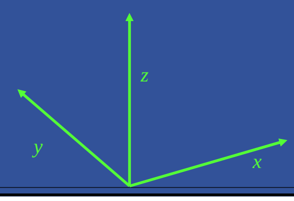
- Growth rates ~ same as in single-phase medium at same ④ρ⑤, provided intercloud separation < λ/2
- Fastest-growing modes have $\gamma \sim \Omega \Rightarrow t_{grow} \sim t_{orbit}$ ~100 Myr
- Clouds grow by agglomeration; strong bends in *B*-field are in clouds
- MRI "channel flow" dominates late stages of 2D models



Piontek & Ostriker (2004)

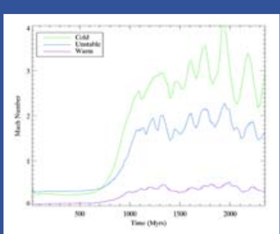
Development of 3D saturated-state turbulence

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

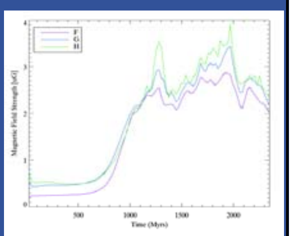


Turbulence history

- Standard model: initial ④n⑤=1 cm^{-3} ; ④B_z⑤=0.26 μG
- Late time: δv_{tot}=2.7 km s^{-1}; δv_x =1.9, δv_y =1.7, δv_z =0.7 km s^{-1}
  B_{tot}=2-3 μG; B_x=1.3, B_y=1.9, B_z=0.5 μG;
  similar values in all phases
- Compare with isothermal model with same ④B_z⑤, ④n⑤, P_{late}:
  δv_{tot}=4 km s^{-1} ; B_{tot}=3.5 μG



velocity



magnetic field

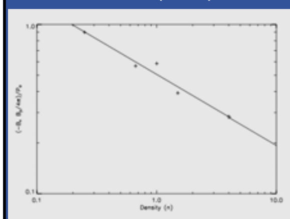
Scalings of saturated-state turbulent stresses

- Vary mean density in the box; other parameters fixed
- ④-$B_x B_y$⑤/P_0∝ ④n⑤$^{-0.4}$
- ④ρ$v_x v_y$⑤/P_0∝ ④n⑤$^{-1.1}$

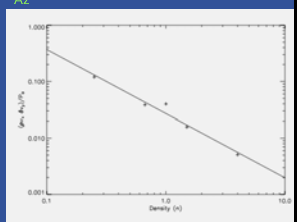
Compare:

HGB(95) stresses ∝$L_z \Omega v_{A,z}/c_s^2$ ∝④n⑤$^{-0.5}$

Sano et al (2004) stresses ∝ $v_{Az}^{3/2}$ ∝④n⑤$^{-0.75}$



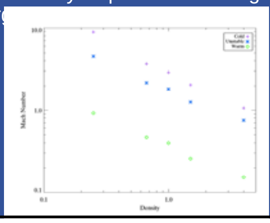
Maxwell stress



Reynolds stress

Saturation scalings of δv

- ④δv²⑤^1/2 = 3 km s^-1 × ④n⑤^-0.77 (or ④n⑤^-0.7 for warm-only);
- this agrees with scaling prediction from equating
  dE/dt_MRI input ~ Ω④-B_x B_y⑤/(4π ④ρ⑤) ∝ ④n⑤^-1.4 with
  dE/dt_collis diss ~ (δv)³ ④ρ⑤/(r_cl ρ_cl) ∝ ④n⑤
- At low ④n⑤, cold cloudlets are trans-sonic with respect to warm medium (up to 8 km s^-1)
- Low- ④n⑤ velocity dispersions are large enough to provide lar



Mach number

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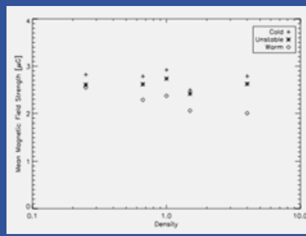
Saturation scalings of B^2

- ④B²⑤ ~independent of ④n⑤, *unlike single-phase results*
- set by ambient pressure in warm phase (β_{sat}~0.5-1)?
- Is saturation at β ~1 because growth rate ~ Ω $\beta_y^{1/2}$ =reconnection rate ~ $v_{A,y}/H$~ Ω $\beta_y^{-1/2}$?



B-field strength

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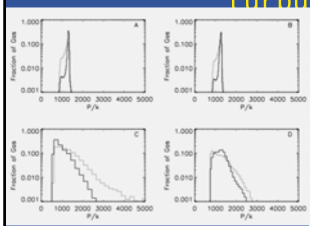
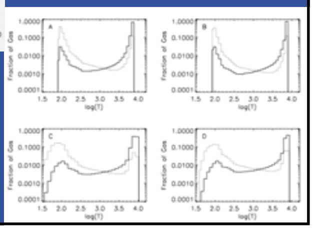
Thermal structure with turbulence



pressure

- Pressure, temperature (& density) PDFs broaden with turbulence
- *Not* "phase continuum"
- Quasi-two-phase state persists since t_{cool}<$t_{turb\ diss}$



temperature

A,B,C,D: t=1,2.5,5,9 orbits

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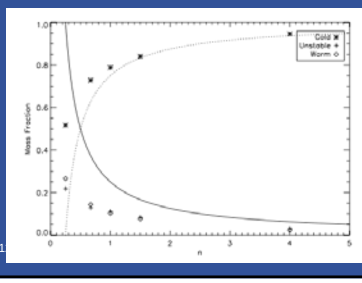
Total mass fractions

- Mass fraction in cold component increases with ④n⑤ ; exceeds static prediction at low ④n⑤ due to turbulent compression
- Thermally-unstable and warm components have comparable mass at all ④n⑤



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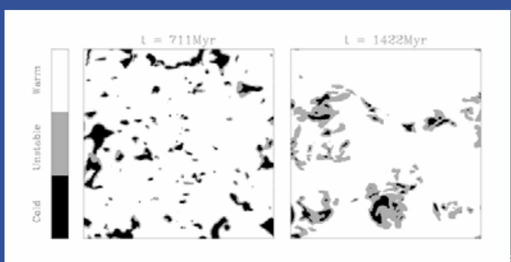
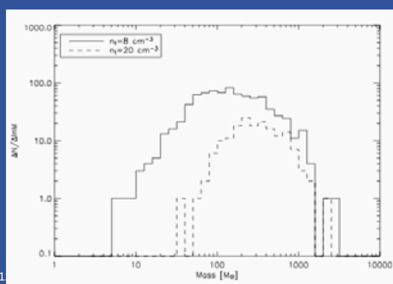
Spatial distribution of thermal phases

- Thermally-unstable gas is in envelopes surrounding cold gas



Cloud mass function

- Characteristic scale M~100-200 $M_\odot$ ⇒ L~5-7 pc, N~2-4 ×10²⁰ cm⁻²
- Similar to Spitzer "standard cloud", ④N(HI)⑤=3 ×10²⁰ cm⁻²
- Consistent with equating t_{shear} =1/Ω
  with t_{collis} = (ρ_{cl} R_{cl}) / (④ρ⑤ v_{rms})



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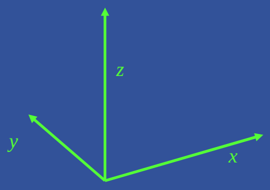
IV. Turbulence and gravity

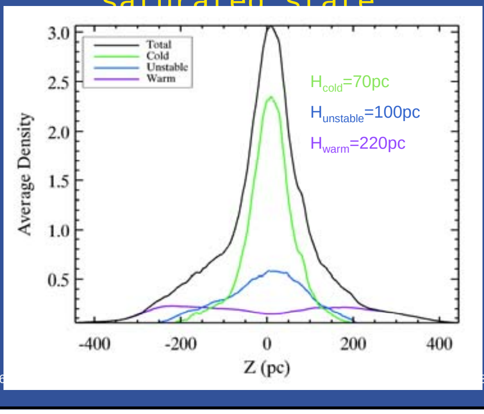
Multiphase gas + MRI+ external **g**

Sample 3D stratified model development

- 256x128x384 box
- t_{max}= 10 orbits =2.5 $\cdot 10^9$ yrs
- $n_{init}(z=0)$ =1 cm^{-3}
- H_{init}=150pc
- Σ_{tot}=10 $M_{\odot} pc^{-2}$



Vertical profile in saturated state



Comparison of turbulent and quiescent states

	Cold mass fraction	Warm mass fraction	Unstable mass fraction	Cold scale height	Warm scale height
quiescent	0.76	0.24	0.01	7pc	240pc
turbulent	0.50	0.25	0.25	70pc	220pc

Vertically-stratified models

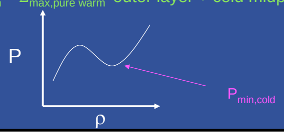
- Gas surface density $\Sigma=10\ M_{\odot}\ pc^{-2}$ for all inner-disk models
- Models vary gravity by a factor of 16:
  - $g \equiv (4\pi G\rho_{eff})\ z \equiv g\ \tilde{z}$, for ρ_{eff} =0.047,0.012,0.003 $M_{\odot}\ pc^{-3}$

Highlights of results:

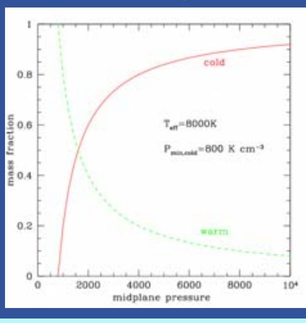
- Mass fractions
  - Cold mass fraction ~60% of total; warm,unstable ~ 20% each; No dependence on $\tilde{g}$
  - Compare to 80-90% of mass in cold component for quiescent disk

    NB: for quiescent disk with $\Sigma > \Sigma_{max,pure\ warm}$=

    expect $\Sigma_{warm} \sim \Sigma_{max,pure\ warm}$ outer layer + cold midplane layer



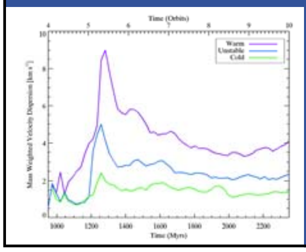
Mass fractions for quiescent disk



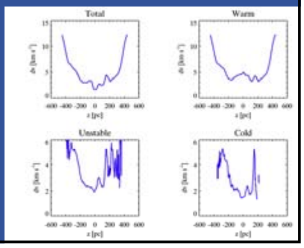
Velocity dispersions

- Mean mass-weighted $\delta v \approx 3$ km/s for all inner-disk (high-Σ) models
- Significant differences in δv between various thermal components, due to stratification

Mean values

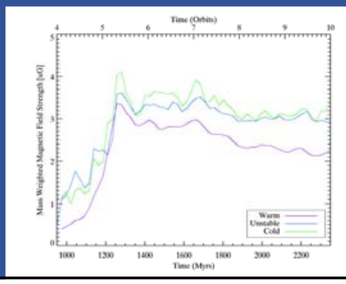


Variation with height



Magnetic field strengths

- Mean magnetic field ~ 3μG, for all g models
- Largest *B* in cold phase, near midplane
- Maximum β~0.4-0.5, near midplane



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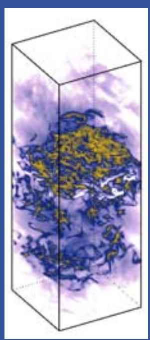
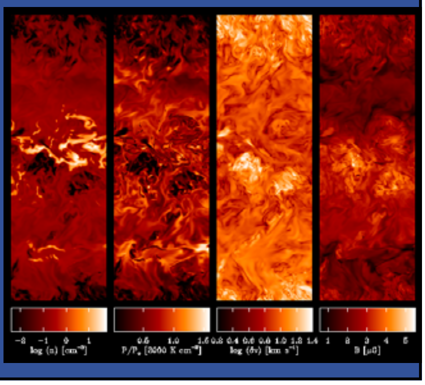
Vertical distributions





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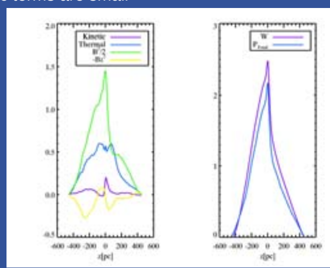
Contributions to vertical support

- Quasi-steady "vertical equilibrium" is established
- Most of midplane support is magnetic when $\Sigma_{cold} > \Sigma_{warm}$
- Upper layers supported by thermal + magnetic pressure
- Kinetic terms are small



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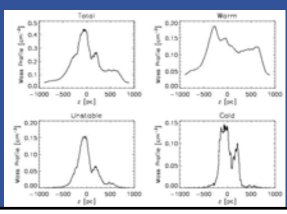
Fractional support against gravity

Outer disk model

- Low surface density Σ_{tot}=6 $M_\odot$ pc^{-2}
- Low gravity ρ_{eff} =0.003$M_\odot$ pc^{-3}
- Results:
  - Low fraction of cold gas (20%)
  - Larger δv~ 5 km/s than for inner-galaxy models
  - Large cold gas scale height

2 kpc



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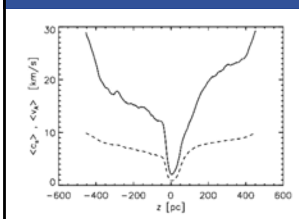
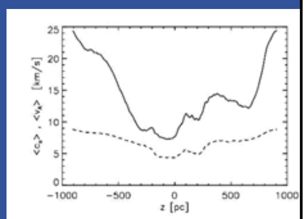
Vertical profiles compared



Inner galaxy model



Outer galaxy model

Low mean midplane density in outer-galaxy case ⇒ $\langle c_s\rangle$, $\langle v_A\rangle$ are large

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Outer-disk star formation thresholds

- Steep drop in SF occurs in outer galactic disks; HI extends farther
- Usually explained as $Q=\kappa c_{eff}/\pi G\Sigma$ falling below some threshold Q_{crit}
  - Consistent with observations using fixed c_{eff} (Kennicutt 1989, Martin & Kennicutt 2001)
- Schaye (2001) argues SF onset coincides with pressure threshold to permit cold atomic phase with c_s=1 km/s (cf. Elmegreen & Parravano 1994)
  - But: observed SF onset is sometimes well inside H_2-dominant radius (MK01)
- New model shows:
  - Due to turbulence, 20% cold gas can be present at radii where thermal pressure is “too low”
  - Magnetic fields are similar to inner-galaxy values
  - Cold gas is kept stirred into warm gas by MRI ; H_{cold} is large
  - Low mean density ⇒ ④v_A⑤ > 8 km/s, ④ c_s ⑤ > 5 km/s even near the midplane
  - If Q includes δv, δv_A and/or ④c_s⑤ in c_{eff} , $Q > Q_{crit}$ in outer disk

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Need to study….

- What is appropriate weighting of σ_{turb} (δv and δv_A) and σ_{therm} in c_{eff} for $L_J=c_{eff}^2/(G\Sigma)$ and $t_J=c_{eff}/(G\Sigma)$ in multiphase gas?
- Are magnetic fields stabilizing or destabilizing in net? What is critical Q ?
- Do star-forming clouds preferentially develop from thermally- and/or dynamically-cold components?

…stay tuned for further results!

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Summary

- Galactic ISM is a turbulent disk system (like big accretion disk!)
- Special characteristic: multiphase, cloudy structure, due to cooling properties
- Have studied turbulence and multiphase structure interaction in Galactic MRI

Saturated-state results for unstratified models:

- Scalings of ④-B_xB_y⑤, ④$\rho v_x v_y$⑤, and ④$\delta v^2$⑤ with ④n⑤ in cloudy gas are similar to single-phase models
- Saturated-state ④$B^2$⑤$^{1/2}$ ≈ 3μG *independent* of ④n⑤, for P_{th}/k ≈ 1000
- Result ④$\delta v^2$⑤$^{1/2}$ ∝ ④n⑤$^{-0.77}$ is consistent with balance of MRI driving with cloud-collision dissipation
- For ④n⑤ characteristic of outer galaxies’ ISM, $\delta v \approx$ 8 km/s
- Turbulent heating broadens, but retains, two-phase thermal structure
- Cold cloud sizes, masses comparable to observations

Stratified models:

- For Solar-nbhd surface density (Σ =10 $M_\odot$ pc $^{-2}$), δv ~ 3 km/s and B ~ 3μG
- Turbulent magnetic pressure lifts cold gas off the midplane only few tens of pc when $\Sigma_{cold} \sim \Sigma_{warm}$ (inner-disk high- Σ models)
- Low- Σ , low- g outer-galaxy model with $\Sigma_{cold} << \Sigma_{warm}$ has thick turbulent cold/warm disk
- Outer-galaxy model has large c_{eff} , $v_{A,}$ and δv at midplane;
  - does this ⇒ $Q>Q_{crit}$ in outer galaxy? Need further study!

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