A Hitchhiker's Guide to Galactic Gastrophysics

Snežana Stanimirović & John Everett

University of Wisconsin–Madison

With insights from the Madison 'ISM Lunch' gang:

Bob Benjamin, Ed Churchwell, Don Cox, Jay Gallagher,
Alex Lazarian, John Mathis, Dan McCammon, Ron Reynolds,
Blair Savage, Linda Sparke, Eric Wilcots, Ellen Zweibel

THE UNIVERSITY of WISCONSIN MADISON

Motivation
- Why Study Galactic Gas Dynamics?

Major ISM Questions: Where do the models stand?

Motivation

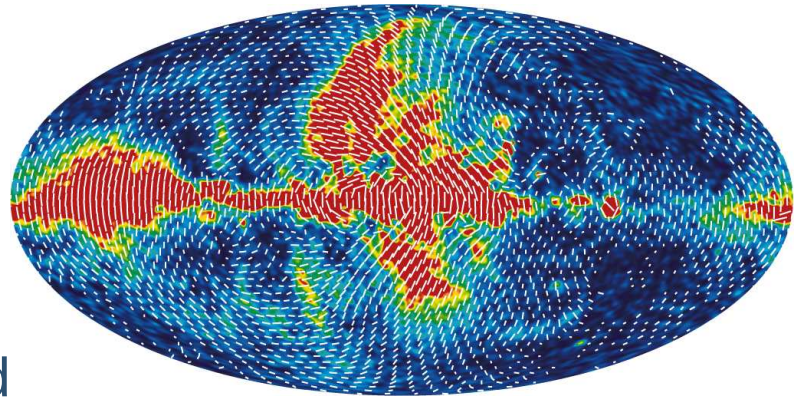
Why Study Galactic Gas Dynamics?

- How does **Galactic Ecology** work? We need to build a detailed foundation for understanding our Galaxy, other galaxies, and galaxy formation & evolution.
  The Milky Way is *the* "Rosetta Stone" where we learn to translate plasma physics into the larger-scale observables we see elsewhere.

Carina Nebula, *Hubble Heritage*

Why Study Galactic Gas Dynamics?

- How does **Galactic Ecology** work? We need to build a detailed foundation for understanding our Galaxy, other galaxies, and galaxy formation & evolution.
- The Interstellar Medium (ISM) is a ready-made laboratory for plasma physicists: many of the processes plasma physicists study are exhibited (in their simpler extremes!) in the ISM.
- Understanding the ISM can also help in those studies for which the Galaxy is a foreground, such as CMB studies.



WMAP K-band (23 GHz)

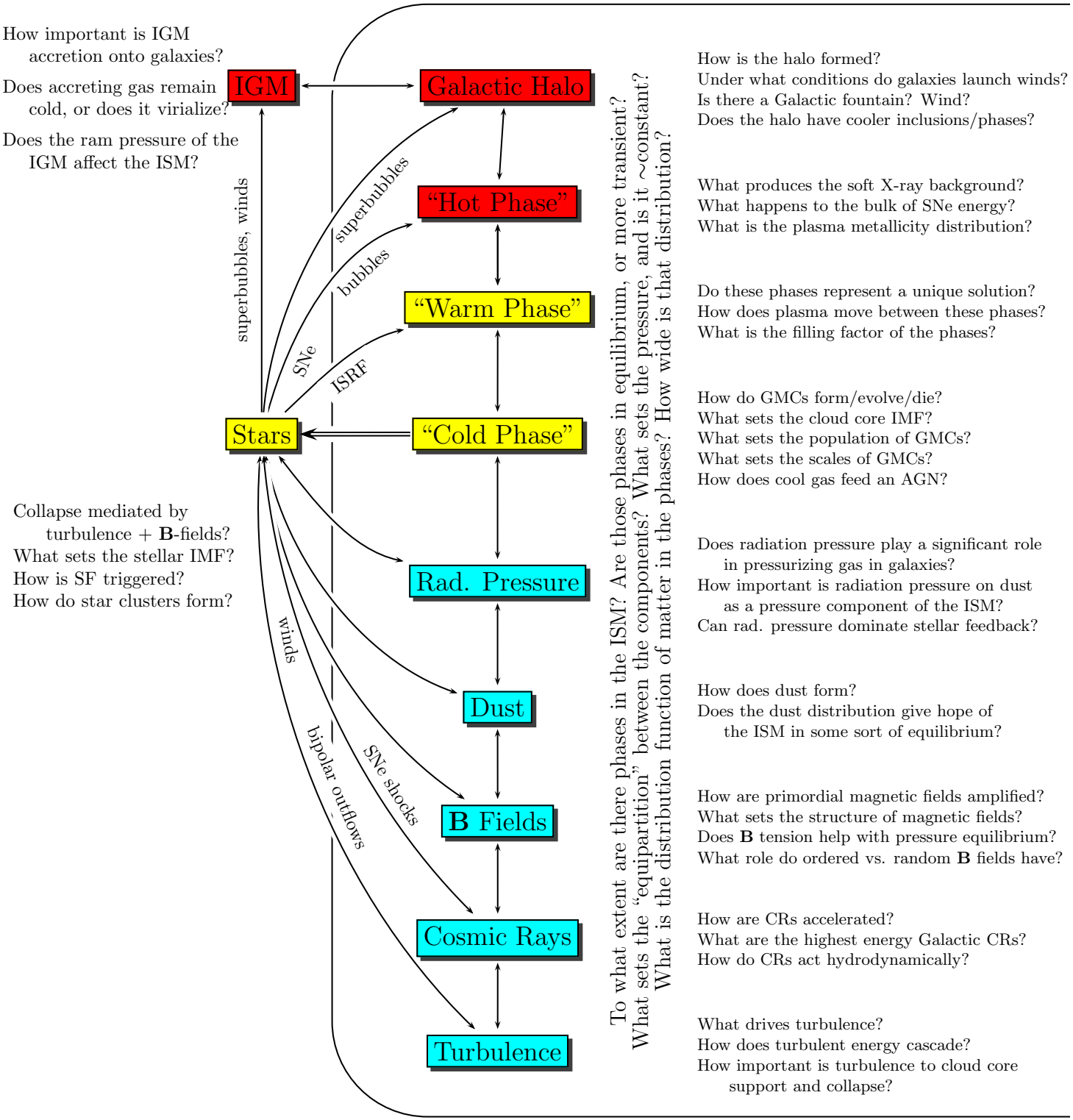
THE UNIVERSITY of WISCONSIN MADISON

Motivation

Major ISM Questions: Where do the models stand?

- Overview of Salient Questions
- How is the Interstellar Medium Structured?
- How does MHD Turbulence work?
- Understanding the Milky Way's Halo
- Overview of Salient Questions

Major ISM Questions: Where do the models stand?


How important is IGM accretion onto galaxies?
Does accreting gas remain cold, or does it virialize?
Does the ram pressure of the IGM affect the ISM?
IGM
Galactic Halo
"Hot Phase"
"Warm Phase"
"Cold Phase"
Stars
Rad. Pressure
Dust
B Fields
Cosmic Rays
Turbulence
superbubbles, winds
superbubbles
bubbles
SNe
ISRF
winds
bipolar outflows
SNe shocks
Collapse mediated by turbulence + B-fields?
What sets the stellar IMF?
How is SF triggered?
How do star clusters form?
To what extent are there phases in the ISM? Are those phases in equilibrium, or more transient?
What sets the "equipartition" between the components? What sets the pressure, and is it ∼constant?
What is the distribution function of matter in the phases? How wide is that distribution?
How is the halo formed?
Under what conditions do galaxies launch winds?
Is there a Galactic fountain? Wind?
Does the halo have cooler inclusions/phases?
What produces the soft X-ray background?
What happens to the bulk of SNe energy?
What is the plasma metallicity distribution?
Do these phases represent a unique solution?
How does plasma move between these phases?
What is the filling factor of the phases?
How do GMCs form/evolve/die?
What sets the cloud core IMF?
What sets the population of GMCs?
What sets the scales of GMCs?
How does cool gas feed an AGN?
Does radiation pressure play a significant role in pressurizing gas in galaxies?
How important is radiation pressure on dust as a pressure component of the ISM?
Can rad. pressure dominate stellar feedback?
How does dust form?
Does the dust distribution give hope of the ISM in some sort of equilibrium?
How are primordial magnetic fields amplified?
What sets the structure of magnetic fields?
Does B tension help with pressure equilibrium?
What role do ordered vs. random B fields have?
How are CRs accelerated?
What are the highest energy Galactic CRs?
How do CRs act hydrodynamically?
What drives turbulence?
How does turbulent energy cascade?
How important is turbulence to cloud core support and collapse?

THE UNIVERSITY of WISCONSIN MADISON

Motivation

Major ISM Questions: Where do the models stand?

- Overview of Salient Questions
- How is the Interstellar Medium Structured?
- How does MHD Turbulence work?
- Understanding the Milky Way's Halo
- Overview of Salient Questions

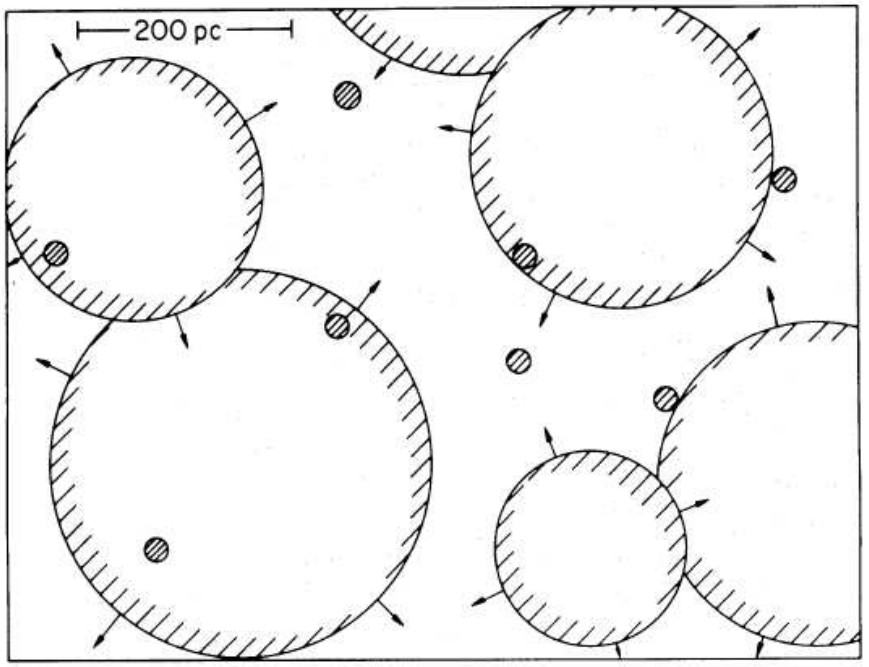
Overview of Salient Questions

- **What is the topology of the ISM, and what are the filling factors of the various phases? How does material transition between phases? Are there really "phases"?**
- **How does MHD turbulence work**? What is the source of turbulent energy, and where does it dissipate? What happens on the smallest scales?
- **What is the structure of the Galaxy's Halo?** What is the nature of the disk/halo interface? Does matter accrete onto the Milky Way? Is there a large-scale Galactic fountain and/or wind? What are High Velocity Clouds? How much does the IGM affect the Milky Way, and vice-versa?
- Where's the edge of the Galaxy?
- How does star formation work? How do Giant Molecular Clouds form?
- How did the magnetic field grow to its observed strength?

How is the Interstellar Medium Structured?

We have only a *very rough* understanding of the filling factors of the various "components" of the ISM. *Knowledge of those components can strongly constrain models:*

- McKee & Ostriker (1977) hypothesized that $f_h \sim 0.7 - 0.8$. McKee (1995) sets $f_h \sim 0.6$.



McKee & Ostriker (1977)

THE UNIVERSITY of WISCONSIN MADISON

Motivation

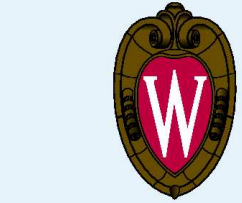
Major ISM Questions: Where do the models stand?

- Overview of Salient Questions
- How is the Interstellar Medium Structured?
- How does MHD Turbulence work?
- Understanding the Milky Way's Halo
- Overview of Salient Questions

How is the Interstellar Medium Structured?

We have only a *very rough* understanding of the filling factors of the various "components" of the ISM. *Knowledge of those components can strongly constrain models:*

- McKee (1995) set $f_h \sim 0.6$ from McKee & Ostriker.
- Slavin & Cox (1993) predicted $f_h \sim 0.2$
- Ferriere (1998) developed analytical models and found $f_h \sim 0.2$ at $R_\odot$. Hypothesized that fractions may change with Galactic radius.
- Simulations by Avillez & Breitschwerdt give $f_h \sim 0.2$.



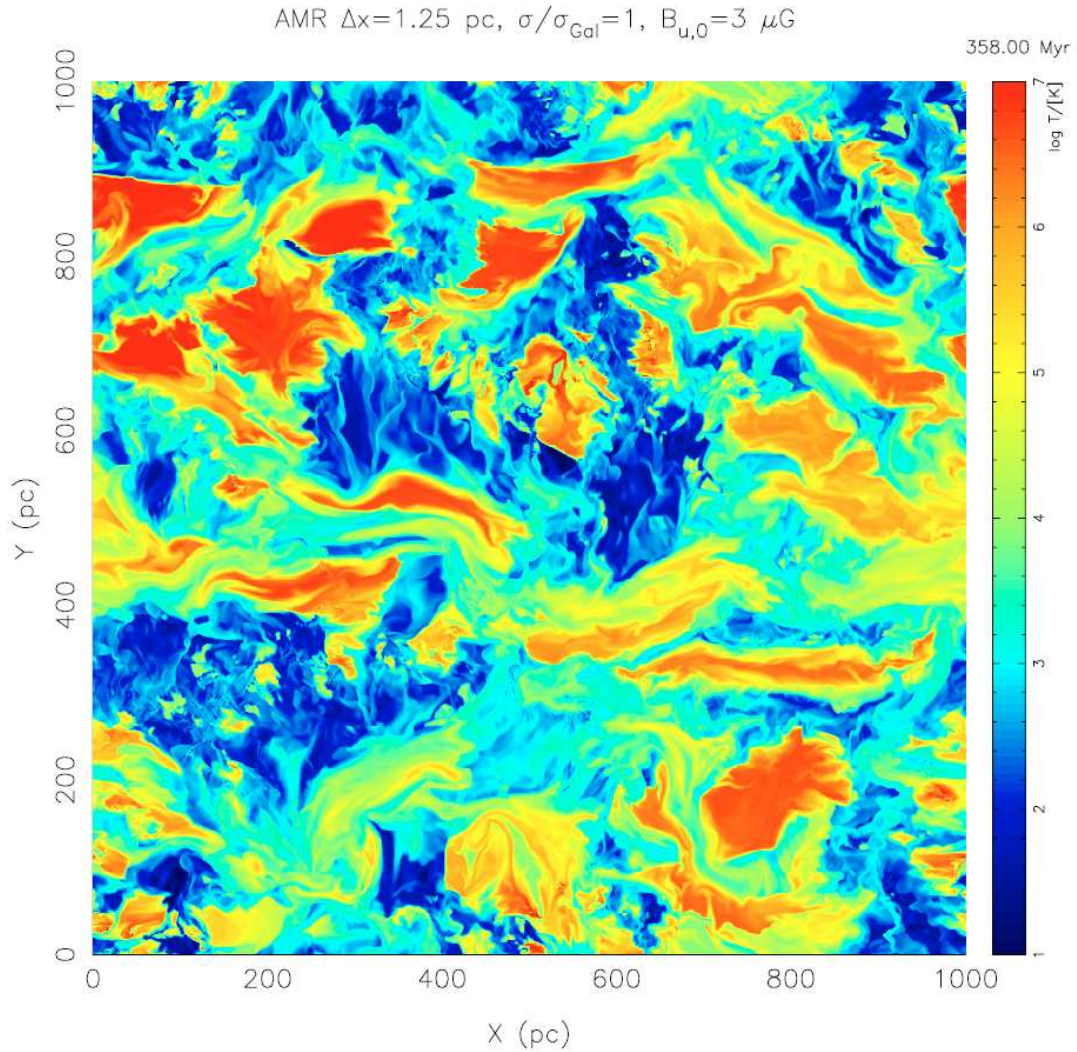
THE UNIVERSITY of WISCONSIN MADISON

Motivation

Major ISM Questions: Where do the models stand?

- Overview of Salient Questions
- How is the Interstellar Medium Structured?
- How does MHD Turbulence work?
- Understanding the Milky Way's Halo
- Overview of Salient Questions

New Turbulent ISM Simulations



Avillez & Breitschwerdt (2005)

THE UNIVERSITY of WISCONSIN MADISON

Motivation

Major ISM Questions: Where do the models stand?

- Overview of Salient Questions
- How is the Interstellar Medium Structured?
- How does MHD Turbulence work?
- Understanding the Milky Way's Halo
- Overview of Salient Questions

How is the Interstellar Medium Structured?

We have only a *very rough* understanding of the filling factors of the various "components" of the ISM. *Knowledge of those components can strongly constrain models:*

- McKee (1995) sets $f_{\mathrm{h,McKee\ \&\ Ostriker}} \sim 0.6$.
- Slavin & Cox (1993) predicted $f_h \sim 0.2$
- Ferriere (1998) developed analytical models and found $f_h \sim 0.2$ at $R_\odot$. Hypothesized that fractions may change with Galactic radius. Wolfire et al. (1995) assumed constant fractions.
- Simulations by Avillez & Breitschwerdt give $f_h \sim 0.2$.
- Simulations by Mac Low and collaborators yield $f_h \sim 0.4$.

There are not yet strong observational constraints on this, but the best constraints on gas filling factors are in the radio: H I holes in M31 (Brinks & Bajaja 1986) and the warm neutral medium observations of Heiles & Troland (2003). Pulsar dispersion measurements of ionized medium?

THE UNIVERSITY of WISCONSIN MADISON

Motivation

Major ISM Questions: Where do the models stand?

- Overview of Salient Questions
- How is the Interstellar Medium Structured?
- How does MHD Turbulence work?
- Understanding the Milky Way's Halo
- Overview of Salient Questions

How does MHD Turbulence work?

The ISM is dynamic! This dynamic nature is rooted in **magnetohydrodynamic (MHD) turbulence**: the ISM is *not* in a static equilibrium (at least in the warmer, less dense, components).

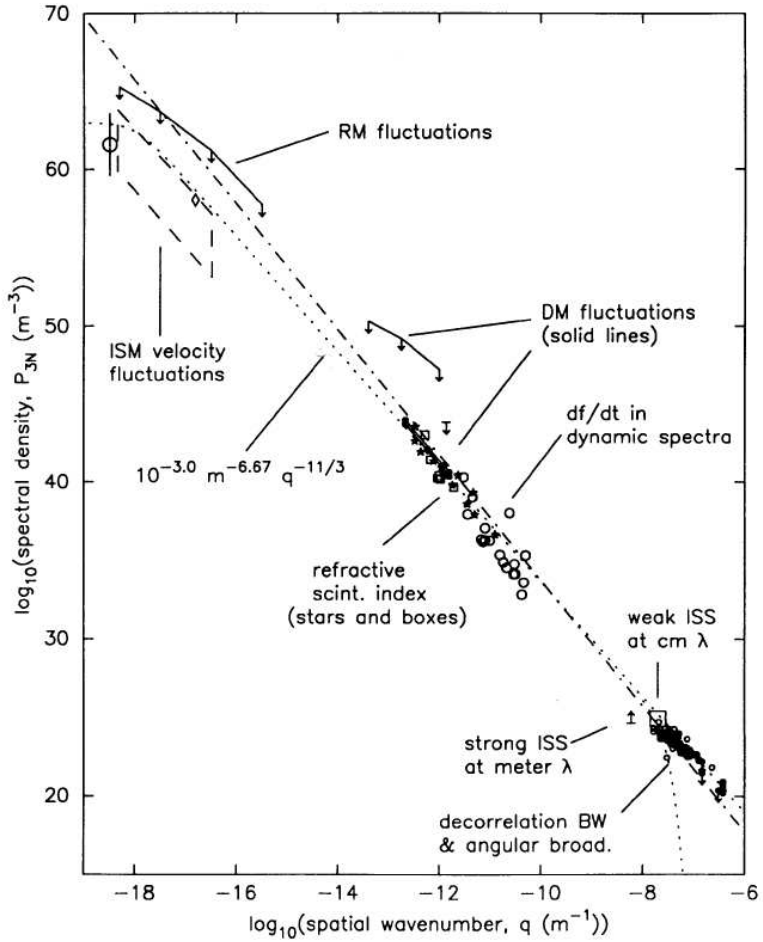
Turbulence is important for:

- **Supplying turbulent mixing & diffusion**
- Providing pressure support for the gas in the disk
- Turbulent models can explain H I observations of Giant Molecular Clouds (Ballesteros-Parades, Avillez, & Mac Low (2000)). So, globally, models seem to be able to explain cloud support.
- On very small scales, turbulence drives compressions that can trigger star formation.
- Turbulence may also explain the wide range of pressures observed (Jenkins & Tripp 2006): Gas can exist in the *thermally unstable regime.*

How does MHD Turbulence work?

Of course, still many open questions about turbulence:

- What drives the turbulence? How does the energy cascade to smaller scales? How does it dissipate?



Spectrum fit with incompressible, hydrodynamic (Kolmogorov) turbulence...

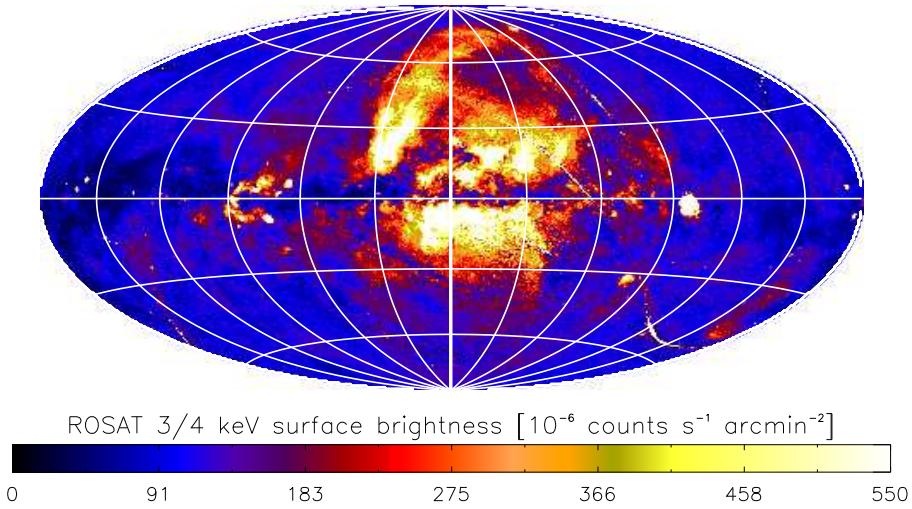
but that doesn't seem to fit what we know about the ISM!
B-fields?
Anisotropy?

Armstrong et al. (1995)

Understanding the Milky Way's Halo

Does the Milky Way need an *Environmental Impact Statement*? Many ISM models show gas flowing into the halo (see Mac Low et al. 2000).

- Does that material fall back to the disk, as a galactic fountain? Might this explain High Velocity Clouds?
- Can plasma escape the Galaxy as a wind with help from Cosmic Rays?



Snowden et al. (1997)
Everett et al. (submitted)

THE UNIVERSITY of WISCONSIN MADISON

Motivation

Major ISM Questions: Where do the models stand?

- Overview of Salient Questions
- How is the Interstellar Medium Structured?
- How does MHD Turbulence work?
- Understanding the Milky Way's Halo
- Overview of Salient Questions

Understanding the Milky Way's Halo

Characteristic of the ISM, studies of the Galactic Halo are related *back* to our two other questions!

Phases: Avillez & Breitschwerdt (2005) claim that the hot gas filling fraction (f_h) is low due to hot gas 'venting' into the halo.

In addition, gas in the halo seems to have multiple phases (McKee 1995), and is surrounded by a more pervasive hot gas.

Turbulence: if the clouds then fall back to the disk, they can impact the disk, feeding back on the ISM and helping to drive turbulence.

The ISM is a Complex System: the current models clearly need observational help to distinguish between them, to provide checks the models.

THE UNIVERSITY of WISCONSIN MADISON

Motivation

Major ISM Questions: Where do the models stand?

- Overview of Salient Questions
- How is the Interstellar Medium Structured?
- How does MHD Turbulence work?
- Understanding the Milky Way's Halo
- Overview of Salient Questions

Overview of Salient Questions

- **What is the topology of the ISM, and what are the filling factors of the various phases? How does material transition between phases? Are there really "phases"?**
- **How does MHD turbulence work**? What is the source of turbulent energy, and where does it dissipate? What happens on the smallest scales?
- **What is the structure of the Galaxy's Halo?** What is the nature of the disk/halo interface? Does matter accrete onto the Milky Way? Is there a large-scale Galactic fountain and/or wind? What are High Velocity Clouds? How much does the IGM affect the Milky Way, and vice-versa?

The Milky Way is a much better computer than any we have available! Arecibo can read important parts of it with great sensitivity.