The Turbulent WIM: Distribution and MHD Simulations

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Warm Ionized Medium

- Major component of the Galaxy:

  space-averaged midplane density \( \langle n_0 \rangle \approx 0.03 \text{ cm}^{-3} \)
  \( n \approx 0.08 – 0.5 \text{ cm}^{-3} \)
  scale height \( h \approx 1 \text{ kpc} \)
  filling factor \( f \approx 0.2 – 0.4 \)
  \( T_e \approx 8000 – 12000 \text{ K} \)

- Observed via pulsar dispersion and pulsar scintillation, and optical recombination (H\(\alpha\), H\(\beta\)) lines and collisionally excited ([O III], [N II], [S II]) lines

  Pulsar dispersion measure \( \text{DM} = \int n \text{ ds} \) (to the pulsar)
  H\(\alpha\) emission measure \( \text{EM} = \int n^2 \text{ ds} \) (to infinity)
WHAM Northern Sky Survey

- Haffner et al. (2003) and http://www.astro.wisc.edu/wham/
- Kinematically resolved map of Galactic Hα emission
  resolution $\sim 12$ km s$^{-1}$
- 37,565 pointings over the northern sky to $\delta \geq -30^\circ$
- One-degree pointings each capture an Hα spectrum to
  $\pm 100$ km/s from the local standard of rest
- Sensitivity below 0.1 R (EM $\sim 0.2$ cm$^{-6}$ pc)
- WHAM will move to the southern hemisphere next year

1 R (Rayleigh) = $10^6/4\pi$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$
• Consider $|b| > 10^\circ$
• Remove sightlines intersecting classical H II regions
• EM sin $|b|$ corrects for path length through the WIM layer
Distribution of EM sin |b|
Distribution of EM $\sin |b|$
Distribution of $\text{EM } \sin |b|$
Distribution of EM $\sin |b|$
Distribution of EM $\sin |b|$
Distribution of EM $\sin |b|$
Distribution of EM sin |b|

- Lognormal distribution
  \[ \langle \log(\text{EM sin } |b|) \rangle = 0.15 \]
  \[ (10^{\langle \log(\text{EM sin } |b|) \rangle} = 1.4 \text{ pc cm}^{-6}) \]
  \[ \sigma_{\log(\text{EM sin } |b|)} = 0.18 \]
- Arises from a multiplicative random walk away from an average value
Isothermal Turbulence

- Lognormal distribution of density is characteristic of multiplicative compressions and rarefactions in a fluid
- WIM is roughly isothermal: $8000 \, K < T < 12000 \, K$ (Haffner, Reynolds, & Tufte 1999)
- WIM is a turbulent, magnetized plasma
- Investigate models of MHD turbulence: Kowal, Lazarian, & Beresnyak (2007)
Isothermal Turbulence Models

- Kowal, Lazarian, & Beresnyak (2007) (KLB)
- 3D compressible, isothermal MHD turbulence
- $256 \times 256 \times 256$ cube
- Range of sonic and Alfvénic Mach numbers ($M_S, M_A$)
- Dimensionless
- We impose physical scaling appropriate to WIM
  $<DM> = 23 \text{ pc cm}^{-3} = 7.1 \times 10^{19} \text{ cm}^{-2}$ (globular cluster pulsars)
  Box sizes from $200 - 1000$ pc
  $T = 8000$ K (from [N II], [S II], and Hα line ratios)
Modeled EM distributions

Subsonic

\( B = 1.0; \ P = 1.00 \)

\( M_s = 0.7 \)

\( M_A = 0.6 \)

Supersonic

\( B = 1.0; \ P = 0.20 \)

\( M_s = 1.4 \)

\( M_A = 0.6 \)

\( B = 1.0; \ P = 0.10 \)

\( M_s = 2.1 \)

\( M_A = 0.6 \)

\( B = 1.0; \ P = 0.01 \)

\( M_s = 6.5 \)

\( M_A = 0.5 \)

Hill et al in prep.
Changing box size changes mean of distribution but not shape or width

Best fit box size is $h = 600$ pc

Turbulent plasma fills $\sim 60\%$ of $h \approx 1000$ pc layer
Gas density

- Local density typically defined as $n_c = \frac{EM}{DM}$ (Reynolds 1991)

- Describes a medium occupying $L_c = \frac{DM^2}{EM}$ with density $n = n_c$; $n = 0$ elsewhere

- Models allow estimates of true local densities

- Lower mean densities (0.03 cm$^{-3}$) and higher filling fraction (0.6)
Conclusions

• WHAM observations show the EM sin $|b|$ distribution of the WIM is lognormal with most probable EM sin $|b| = 1.4$ pc cm$^{-6}$

• Isothermal MHD simulations produce an EM distribution which matches that of the WHAM data well for mildly supersonic ($M_s \sim 1.5 – 2.5$) turbulence

• WIM plasma has typical, local densities of $n \approx 0.03$ cm$^{-3}$ and fills 60% of the volume within a 2 kpc-thick layer about the midplane (in the context of the model)
Future work

• Modelling
  Density stratified model atmosphere
  Model with radiative cooling
  Realistic driving force

• Observational
  Magnetic field probes (rotation measure)
  Better angular resolution (SHASSA)
Scale height of WIM

- Two observational methods

  Dispersion measures of high-latitude pulsars with DM-independent distance measurements (Reynolds 1989, Gomez et al 2001)

  EM vs. $|z|$ in Perseus arm (Haffner, Reynolds, & Tufte 1999)

- Both yield $h = 1$ kpc
Visualizations of models

simulated log EM (pc cm$^{-6}$) ($M_\odot = 1.4; M_A = 0.6$)

buffer = 100 pc

WIM – EM distribution – MHD models

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