THE FIFTH ISM PHASE

as revealed by

FARADAY ROTATION

Carl Heiles, UC Berkeley

OUTLINE OF THIS TALK

ISM Phases –

- **The Four Classical Phases: CNM, WNM, WIM, HIM. What's the history, why does it matter?**
- **The Fifth Phase: WPIM**
- **The Fifth Phase and the Magnetic Field**

A SMALL CLOUD (M/O 1977)

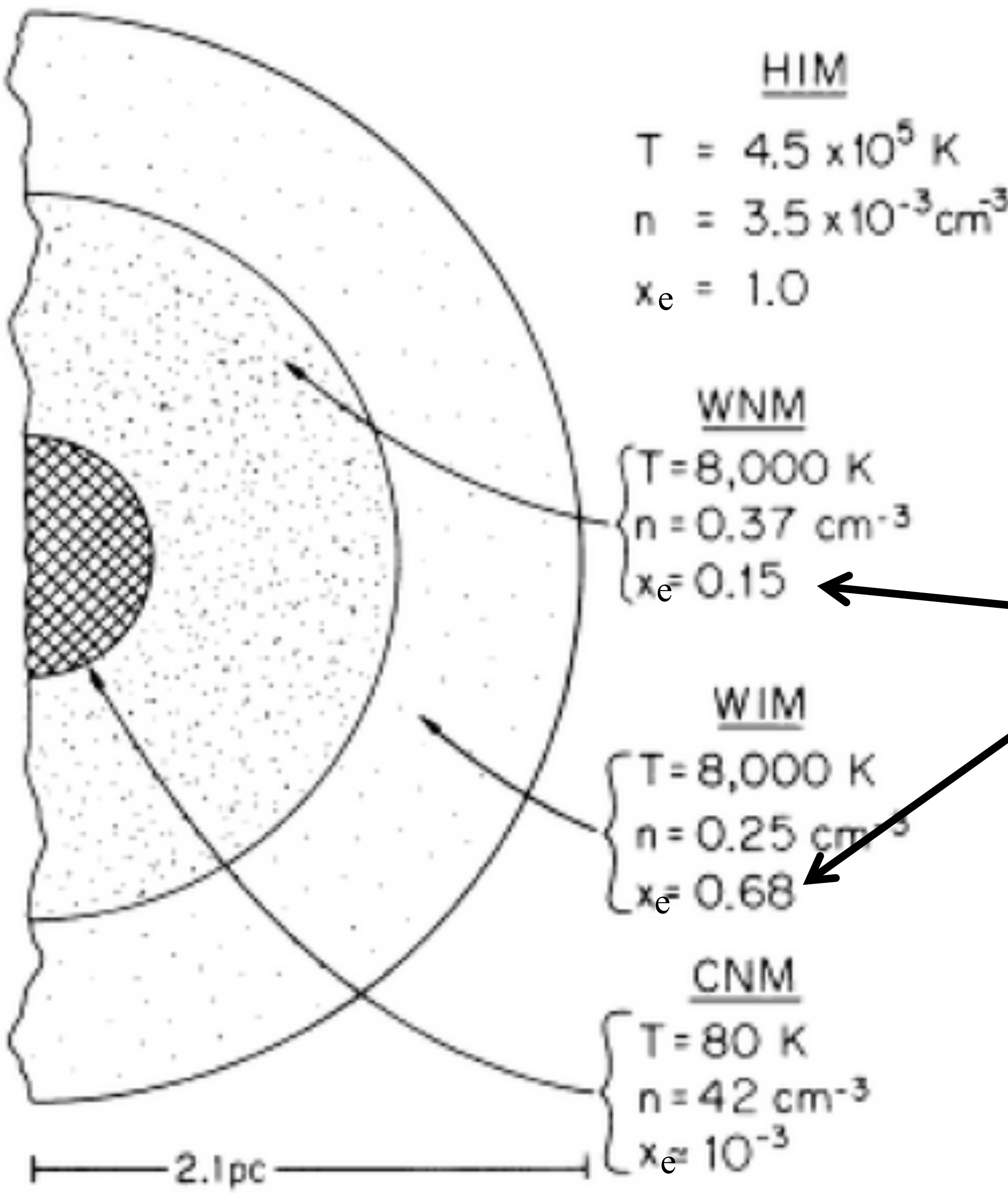


FIG. 1

IONIZATION AGENT:

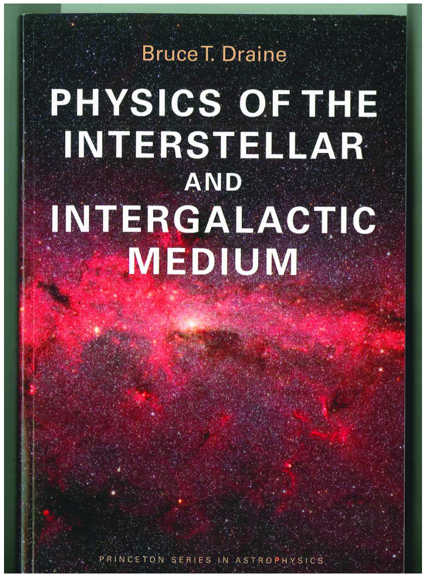
Collisional

Cosmic Rays, Soft X-rays

PARTIALLY ionized!

Soft X-rays, Cosmic Rays

Cosmic Rays, C+



(Brand-new 2011 textbook)

Table 1.3 Phases of Interstellar Gas

Phase	T(K)	n_H(cm^{-3})	Comments
Coronal gas (HIM) $f_V \approx 0.5?$ $\langle n_H \rangle f_V \approx 0.002\,\mathrm{cm}^{-3}$ ($f_V \equiv$ volume filling factor)	$\gtrsim 10^{5.5}$	~ 0.004	Shock-heated Collisionally ionized Either expanding or in pressure equilibrium Cooling by: ◇ Adiabatic expansion ◇ X ray emission Observed by: • UV and x ray emission • Radio synchrotron emission
H II gas $f_V \approx 0.1$ $\langle n_H \rangle f_V \approx 0.02\,\mathrm{cm}^{-3}$	10^4	$0.3 - 10^4$	Heating by photoelectrons from H, He Photoionized Either expanding or in pressure equilibrium Cooling by: ◇ Optical line emission ◇ Free–free emission ◇ Fine-structure line emission Observed by: • Optical line emission • Thermal radio continuum
Warm H I (WNM) $f_V \approx 0.4$ $n_H f_V \approx 0.2\,\mathrm{cm}^{-3}$	~5000	0.6	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Pressure equilibrium Cooling by: ◇ Optical line emission ◇ Fine structure line emission Observed by: • H I 21 cm emission, absorption • Optical, UV absorption lines
Cool H I (CNM) $f_V \approx 0.01$ $n_H f_V \approx 0.3\,\mathrm{cm}^{-3}$	~ 100	30	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Cooling by: ◇ Fine structure line emission Observed by: • H I 21-cm emission, absorption • Optical, UV absorption lines
Diffuse H_2 $f_V \approx 0.001$	~ 50 K	~ 100	Heating by photoelectrons from dust

The original four phases, as defined by McKee & Ostriker, are not the four we think of today.

Today it's:

***The essentially <u>FULLY NEUTRAL</u> CNM and WNM**

***The essentially <u>FULLY IONIZED</u> WIM and HIM**

1.3. The Five Phases

We summarize these five phases' physical properties in Table 1, which is an update and expansion of Table 1 of Heiles (2001). The table includes column densities for a typical individual cloud (N_{typ}) and through the Galaxy for a vertical ($b = 90°$) sightline extending to infinity ($N_{\perp}$) .

Table 1: Properties of phases

Property	CNM	WNM	WIM	WPIM[1]	HIM Erid[2]
P_{th}/k (cm^{-3} - K)	4000	4000	4000	2000	50000
T (K)	50	6000	8000	7000	1.5 $\times 10^6$
n_{Hn} (cm^{-3})	80	0.7	0.25	0.2	0.015
x_e	2×10^{-4}	$\lesssim 1 \times 10^{-2}$	1	0.5 ± 0.49	1
$N_{typ,Hn,20}$	0.5	1	0.08	0.06	0.06
$\boldsymbol{N_{typ,e,20}}$	1 $\times 10^{-4}$	$\lesssim 1 \times 10^{-2}$	0.08	0.03	0.06
$N_{\perp,Hn,20}$	1.5	1.5	1.0	?	—
$\boldsymbol{N_{\perp,e,20}}$	3×10^{-4}	$\lesssim 1.5 \times 10^{-2}$	1.0	?	—

The subscript Hn means N-nuclei (i.e., both neutral and ionized H).

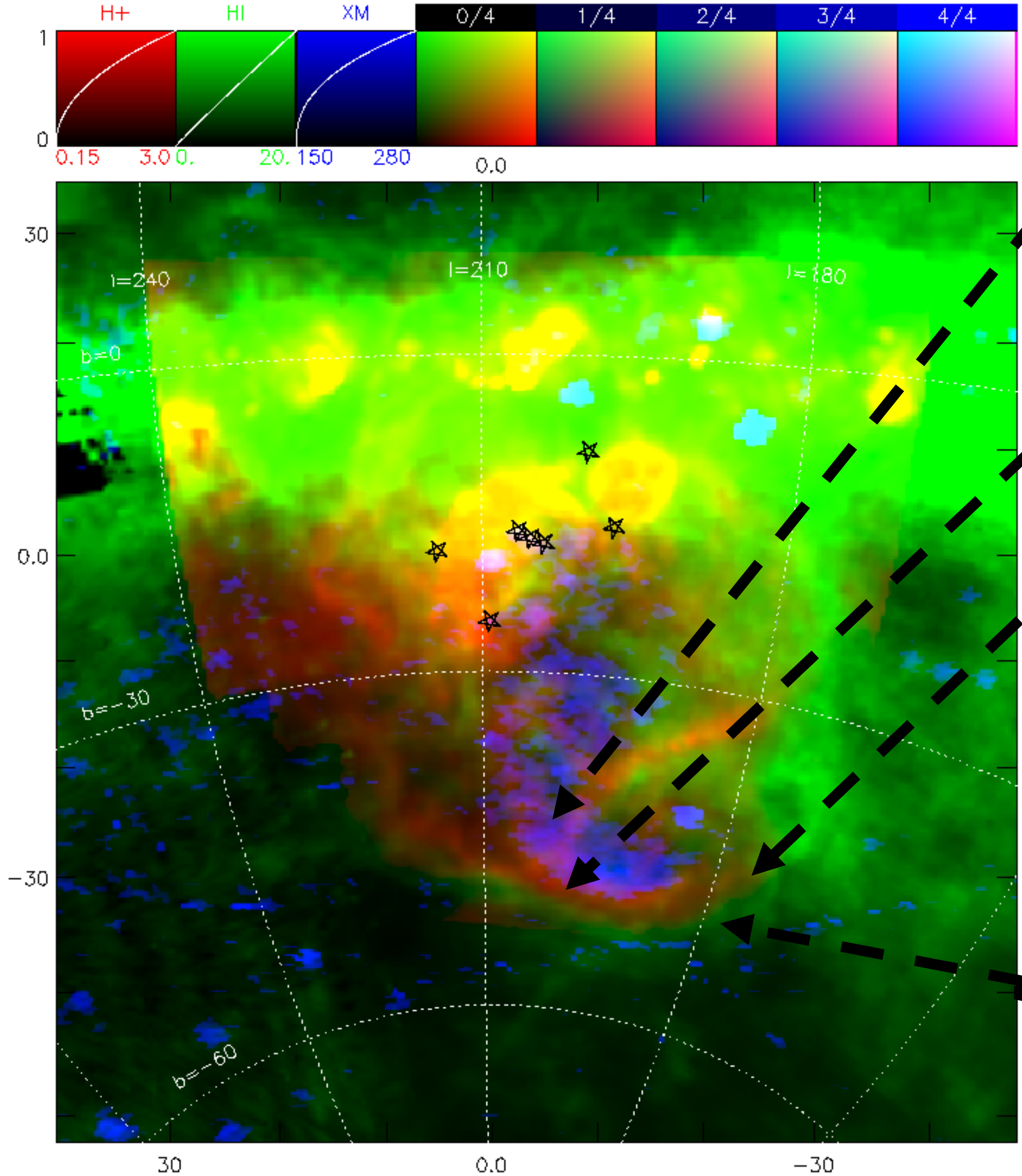
The subscript $\perp$ means line-of-sight at Galactic latitude 90°.

The subscript typ means a typical individual structure.

(1) From Redfield & Linsky (2004, 2008).

(2) For the Orion/Eridanus superbubble (Guo et al. 1995).

Current View: The Four Phases…and the ***FIFTH***



HIM:
T ~ 2 x 10^6 K
x_e = 1; Collisional

WIM:
T ~ 0.8 x 10^4 K
x_e = 1; Stellar UV

WPIM:
T ~ 0.5 x 10^4 K
x_e ~ 0.1 – 0.9;
Soft XR (from HIM),
Stellar UV

WNM:
T ~ 0.5 x 10^4 K
x_e ~ 10^{-2}; Cosmic Rays

CNM:
T ~ 50 K
x_e ~ 10^{-4}; Carbon+

1. INTRODUCTION: FIVE PHASES OF THE DIFFUSE ISM

1.1. The Four "Classical" Phases

The current view of the diffuse Interstellar Medium recognizes four major phases. They are either almost fully ionized or almost neutral. The neutral phases come in two flavors, the Cold and Warm Neutral Media (the CNM and WNM), which have typical temperatures ~ 50 and 5000 K. In the CNM, free electrons come largely from ionized Carbon; in the WNM, from cosmic- and X-ray ionization. The ionized phases also come in two flavors, the Warm and Hot Ionized Media (the WIM and the HIM), which have typical temperatures ~ 8000 and $\gtrsim 10^6$ K. In the WIM, free electrons are produced by UV starlight ionization of H atoms; in the HIM, from collisional ionization of H and other atoms/ions.

1.2. The Fifth Phase

There lurks a fifth phase, the Warm Partially Ionized Medium (WPIM). The WPIM is not widely recognized, mainly because it's presence is hard to establish observationally, but it might be much more common than generally realized. Heiles (2001) reviewed the evidence for and physical properties of this phase, which he called the McKee/Ostriker WIM (MOWIM). It is well represented by the Local Interstellar Cloud (LIC), whose properties are very well specified in a wonderful series of papers by Redfield and Linsky (e.g. 2004, 2008). It presence is also inferred from optical and UV absorption line spectra of stars, particularly in the excellent series of papers by Fitzpatrick and Spitzer (e.g. 1997).

The WPIM is neither mainly neutral nor ionized; typically, its ionization fraction $x_e = \frac{n_e}{n_{Hn}}$ might lie in a wide range, say 0.01 to 0.99. (The subscript Hn means H-nuclei, i.e. both neutral and ionized H). The LIC, for example, has $x_e \sim 0.5$. Being partially ionized means, also, that it is

My recent (Nov 2010) NSF proposal…

NSF Reviewer Nr 1. This gal obviously is a true expert with an inquisitive scientific spirit and knows what she's talking about!

This proposal makes a compelling case that a 5th phase is prevalent in the ISM: the Warm Partially Ionized Medium (WPIM). The PI's new realization that rotation measures (RMs) can be used to study this 5th phase finally gives us a chance to investigate it in detail, answering basic questions like: How common is it in comparison to the Warm Neutral Medium? What produces it? How do magnetic field properties vary from phase to phase in the ISM?

The preliminary studies presented give a good sense of the potential of this new approach. The PI has a well-considered plan to begin with archival data, and supplement with new observations as necessary. In addition, the physical picture will be clarified with supplementary Zeeman splitting measurements.

The PI is well-versed in polarization measurements, and has the expertise to analyze the data. Access to the main observational facility is assured, and successful applications to one or more of the other facilities is likely. One possible issue is that only 7 structures have thus far been identified for study; this is not statistically sufficient, but it is difficult to evaluate how many other suitable regions exist without further investigation.

This project has the potential to significantly alter our understanding of the Galactic ISM. It is hard to say in advance exactly how important this phase is to interstellar modeling, but the fact that it is producing RMs approximately 10 times larger than na´ve expectations suggests it should not be ignored.

NSF Reviewer Nr 2. This guy is a bit less expert (i.e., less effusive), but he still knows what he's talking about!

This is an exciting and original idea. The proposed research has the potential to definitively establish the existence of the 'Fifth Phase', characterize it properties, and conduct a survey of the Galaxy. Doing it using the Faraday rotation is elegant. It also fits nicely into the rapidly advancing sequence of new and important FR results (e.g. expect to be able to start mapping the B-fields in the Warm-Hot Intergalactic Medium).

What are the broader impacts of the proposed activity?

The ISM is obviously central to a broad range of astrophysical problems, and a better insight in its properties will have a long-range broad impact.

Heiles also has a very successful outreach and education program, which merits continued support.

Summary Statement

I reserve final judgment until we have had the opportunity to discuss it. I would say it deserves support: (1) excellent science, (2) broad impact, (3) simple application of variety of survey databases, (4) excellent Outreach/Education program.

NSF Panel Summary. The other panel members don’t even know the concept of “phase” and the astrophysical difficulty of maintaining partial ionization. Not to mention speculation on my ability to manage my time and responsibilities!

Weaknesses:
(1) There was scepticism that the property of partial ionization really represents a completely novel aspect of interstellar gas. Instead, it seems likely that the degree of ionization varies like other parameters throughout the ISM, and regions which conventionally are considered as totally ionized or totally neutral, like the cold neutral medium or warm ionized medium, have a considerable range in the degree of ionization.
(2) There was concern that Professor Heiles is too occupied with existing responsibilities, such as bringing to fruition a project funded in a previous NSF award, as well as his responsibilities as observatory director, to take on a major new project like this.

Tatyana Gavrilchenko---the undergrad sophomore I would have hired for this project had I received funding…

Let’s start with the CNM and WNM.

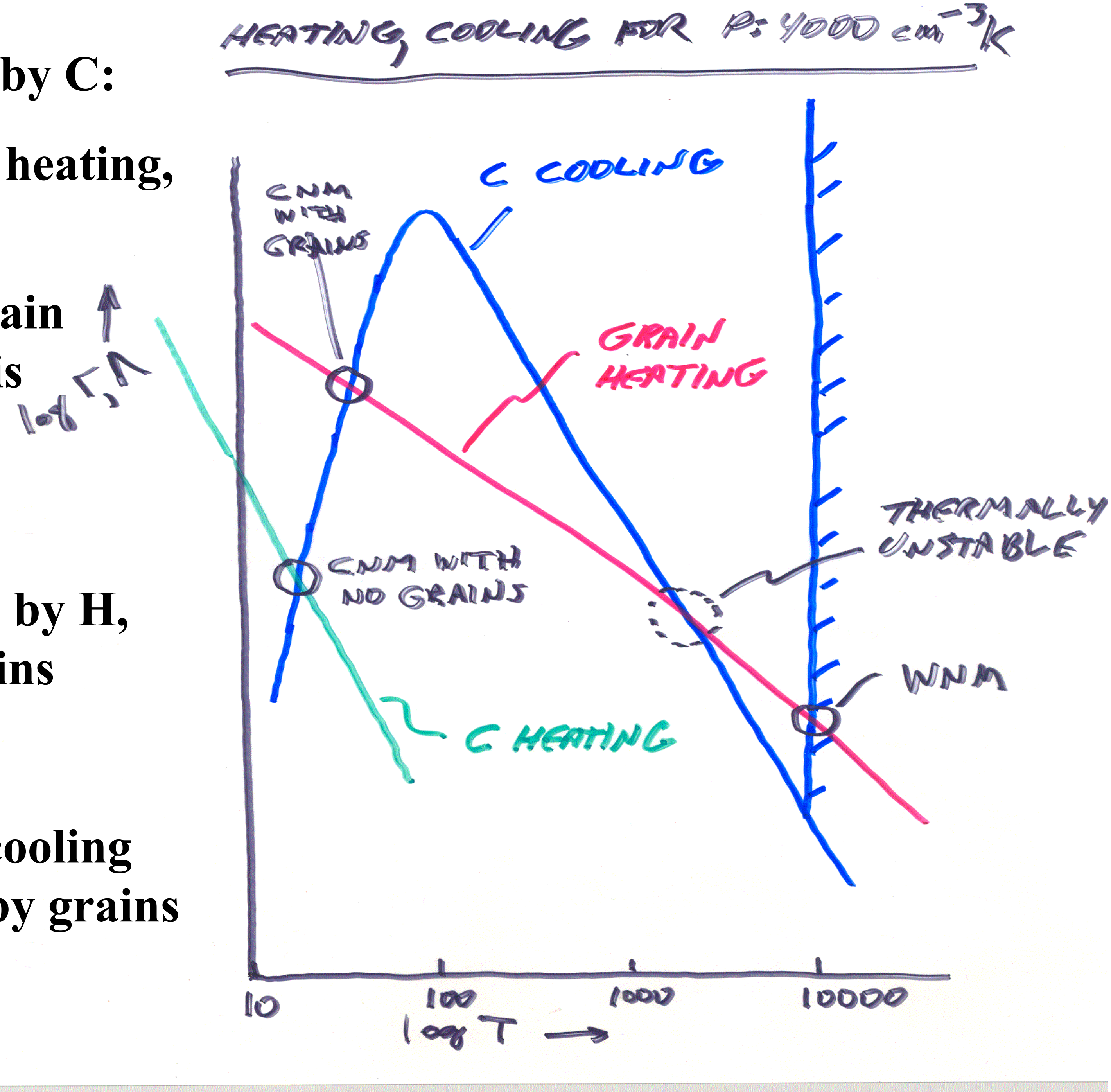
CNM: cooling by C:

With ONLY C heating, temp is 16 K.

With ALSO grain heating, temp is ~50 K

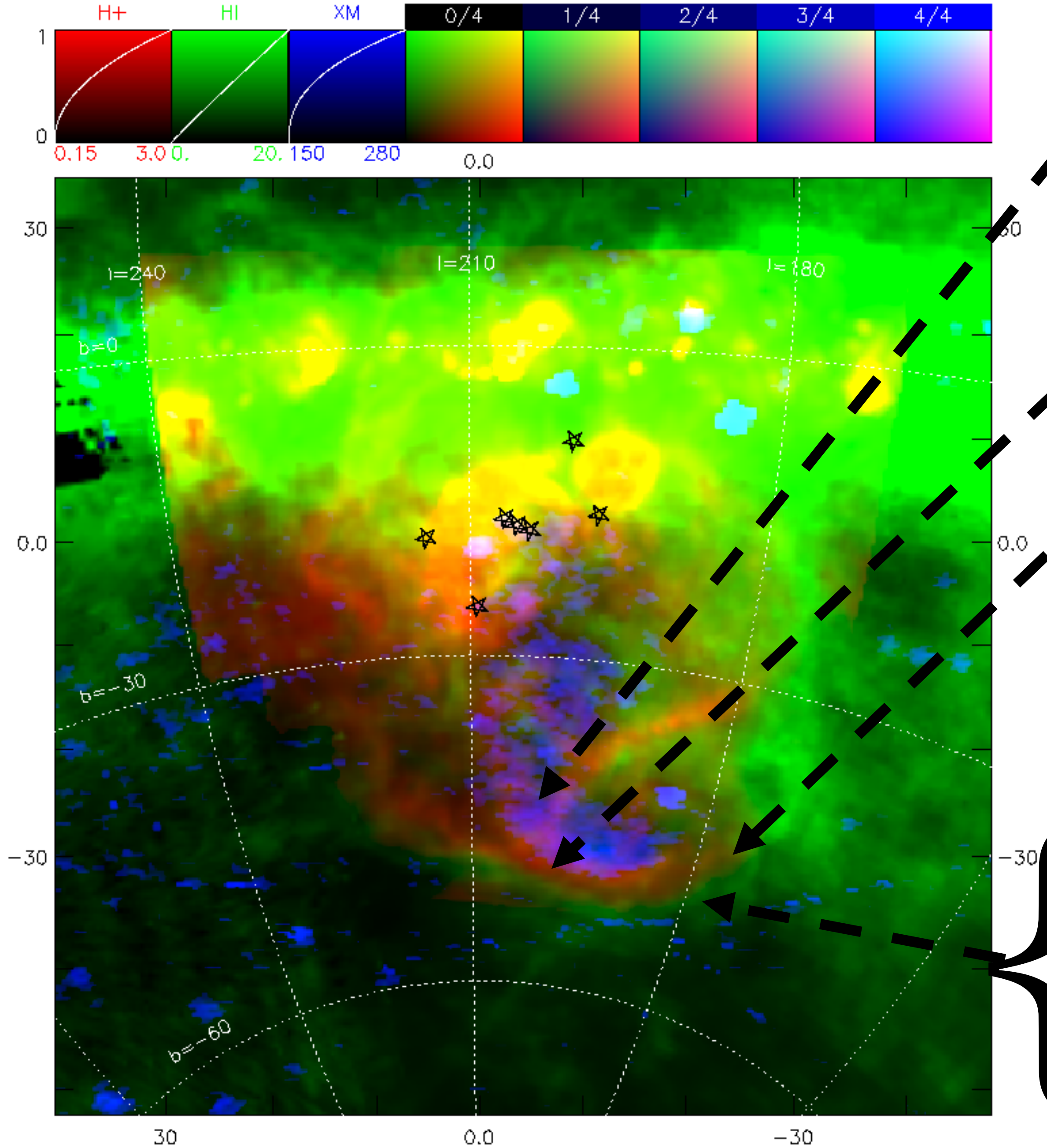
WNM: cooling by H, heating by grains

UNSTABLE: cooling by C, heating by grains



Now let’s consider the WIM and HIM.

Current View: The Four Phases…and the *FIFTH*



HIM:
$T \sim 2 \times 10^6$ K
$x_e = 1$; Collisional

WIM:
$T \sim 0.8 \times 10^4$ K
$x_e = 1$; Stellar UV

WPIM:
$T \sim 0.5 \times 10^4$ K
$x_e \sim 0.1 – 0.9$;
Soft XR (from HIM),
Stellar UV

WNM:
$T \sim 0.5 \times 10^4$ K
$x_e \sim 10^{-2}$; Cosmic Rays

CNM:
$T \sim 50$ K
$x_e \sim 10^{-4}$; Carbon+

The WIM is starlight photoionized, x_e~1.0, like HII regions…

***``High" emission measure [n_e N_e], hence high H-alpha (WHAM) visibility**

***Lowish N_e**

The *Fifth Phase* WPIM is probably XR photoionized, x_e~0.5 +/- 0.45…

***Lowish emission measure [n_e N_e]**

***Larger N_e**

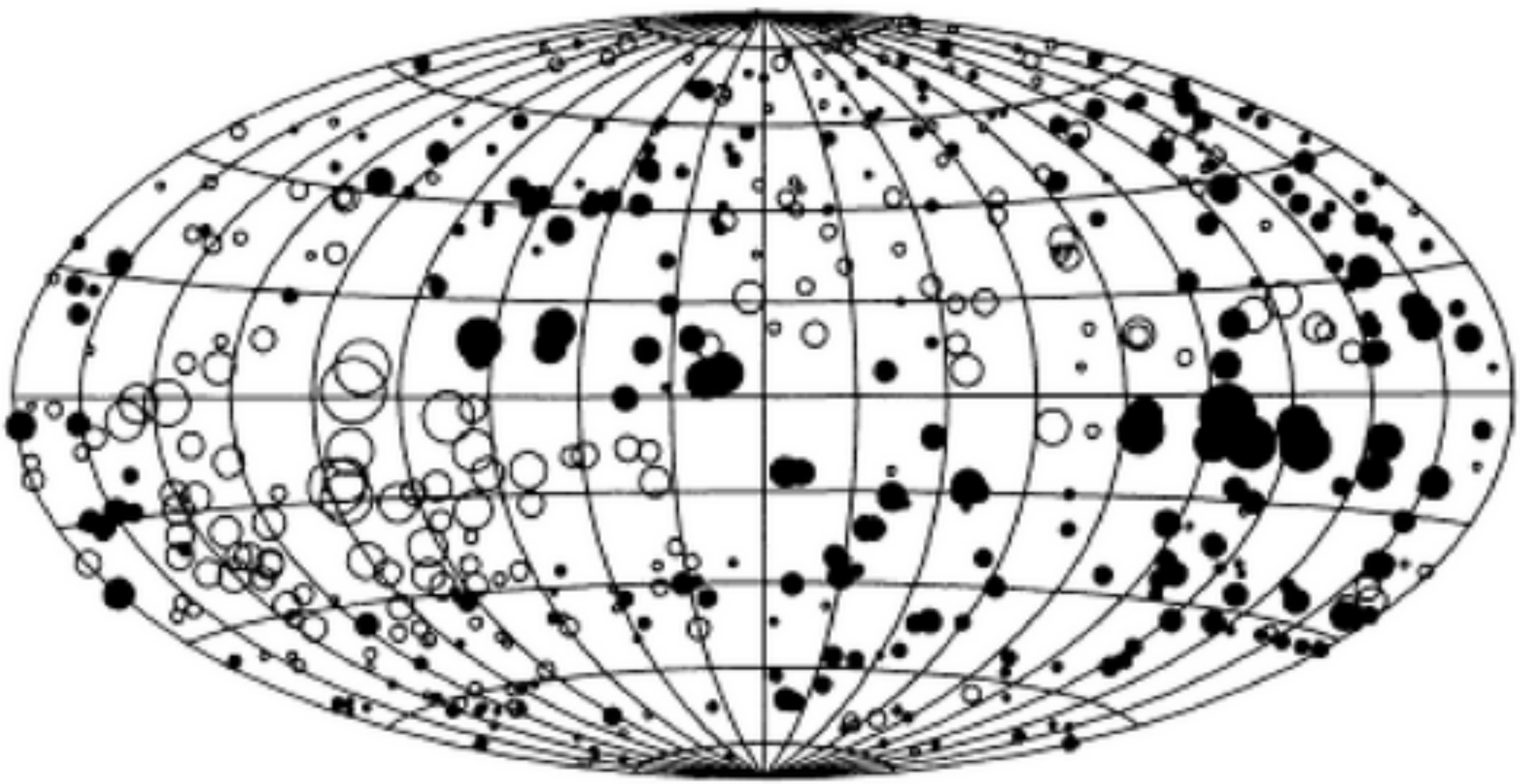
***The ``Local Interstellar Clouds" (LIC – Redfield & Linsky) are WPIM, with x_e~0.5.**

The Faraday Rotation Measure

$$RM \approx N_e B$$

With its larger N_e, is the *<u>Fifth Phase</u>* (WPIM) visible in RM?

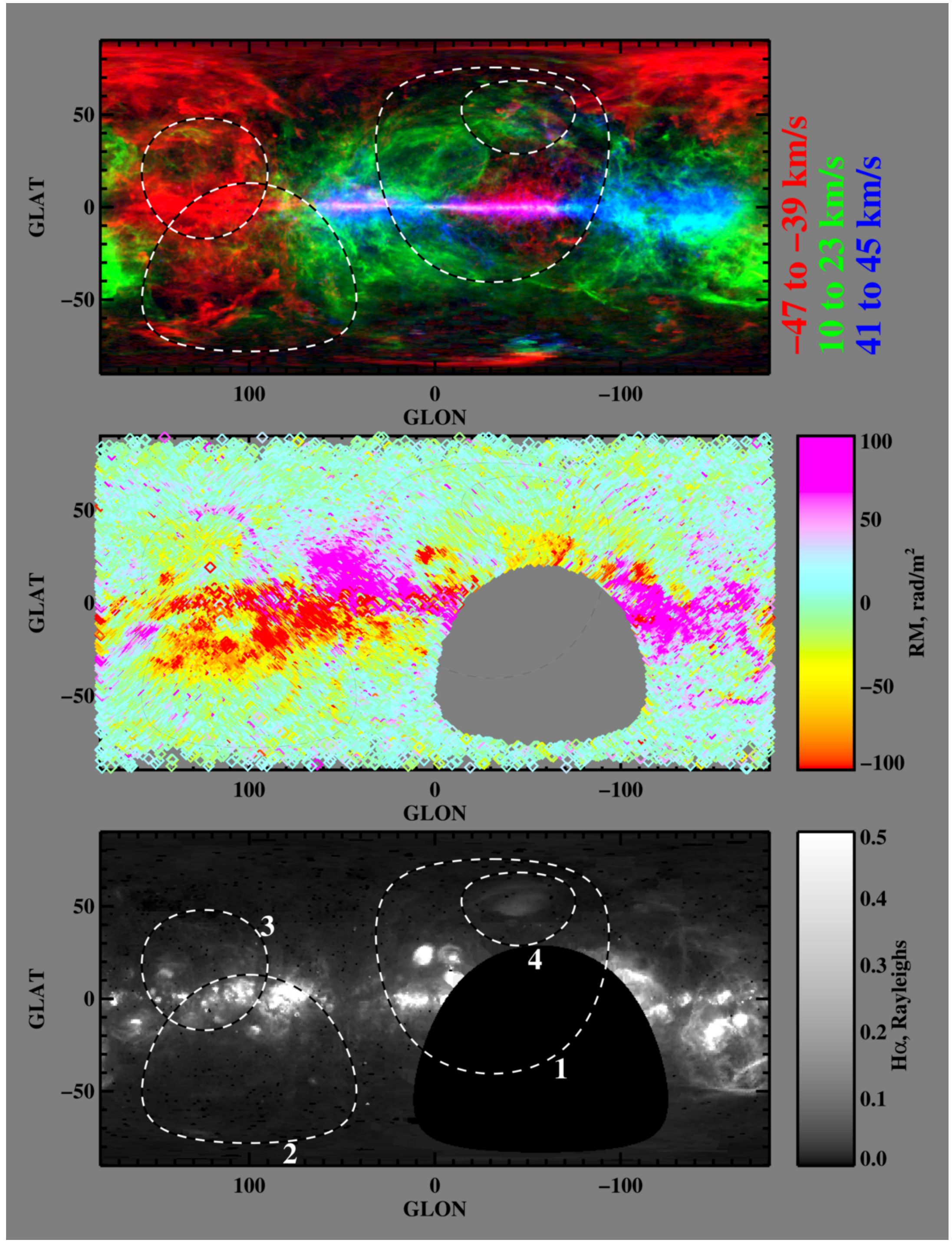
Taylor, Stil, Sumsrum (2009 derived 'best guess' RMs for all 37,543 NVSS sources. Most of these RMs are correct. They allow a detailed mapping of RM on the sky. This is a MAJOR ADVANCE. To understand this, we first look at the RM distribution given by Oren & Wolfe (1995)—for 499 sources…

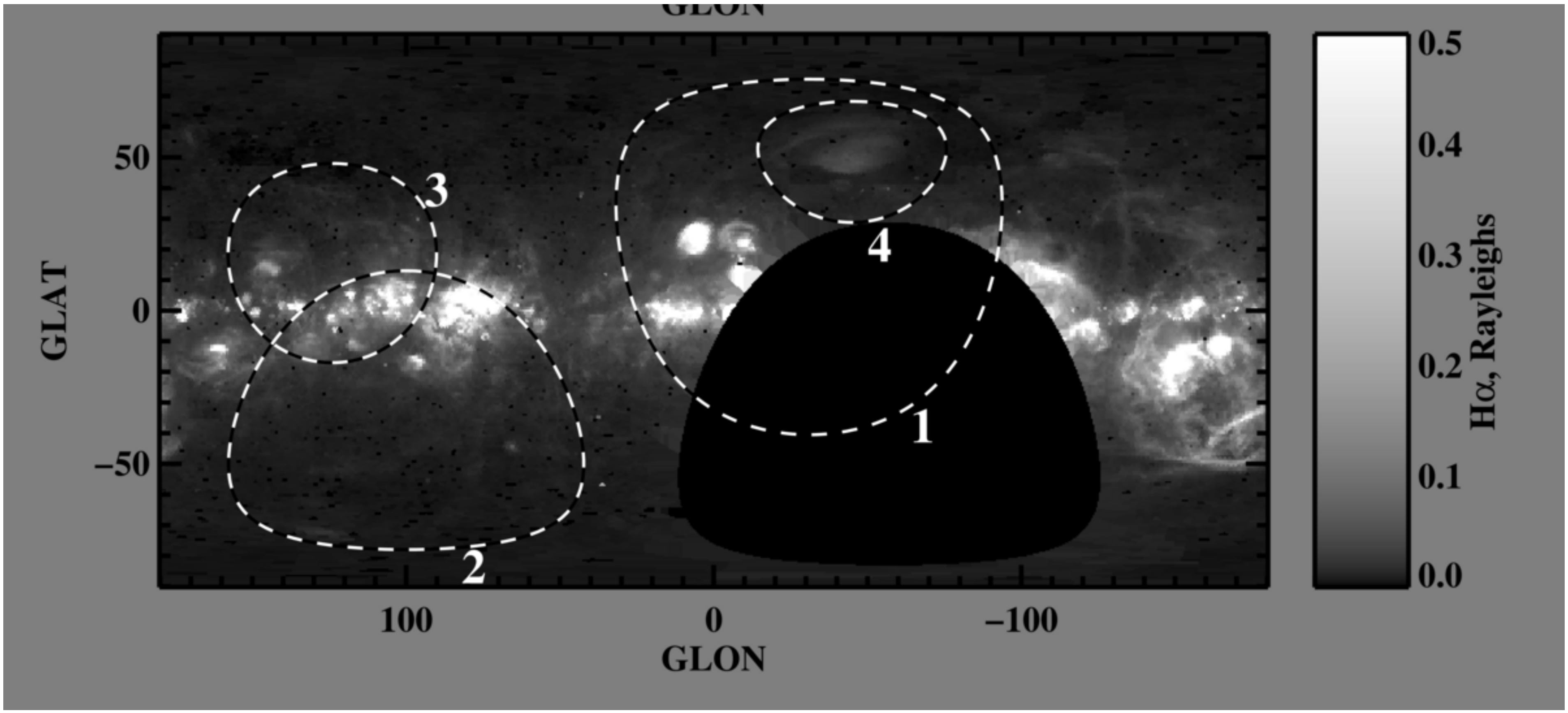


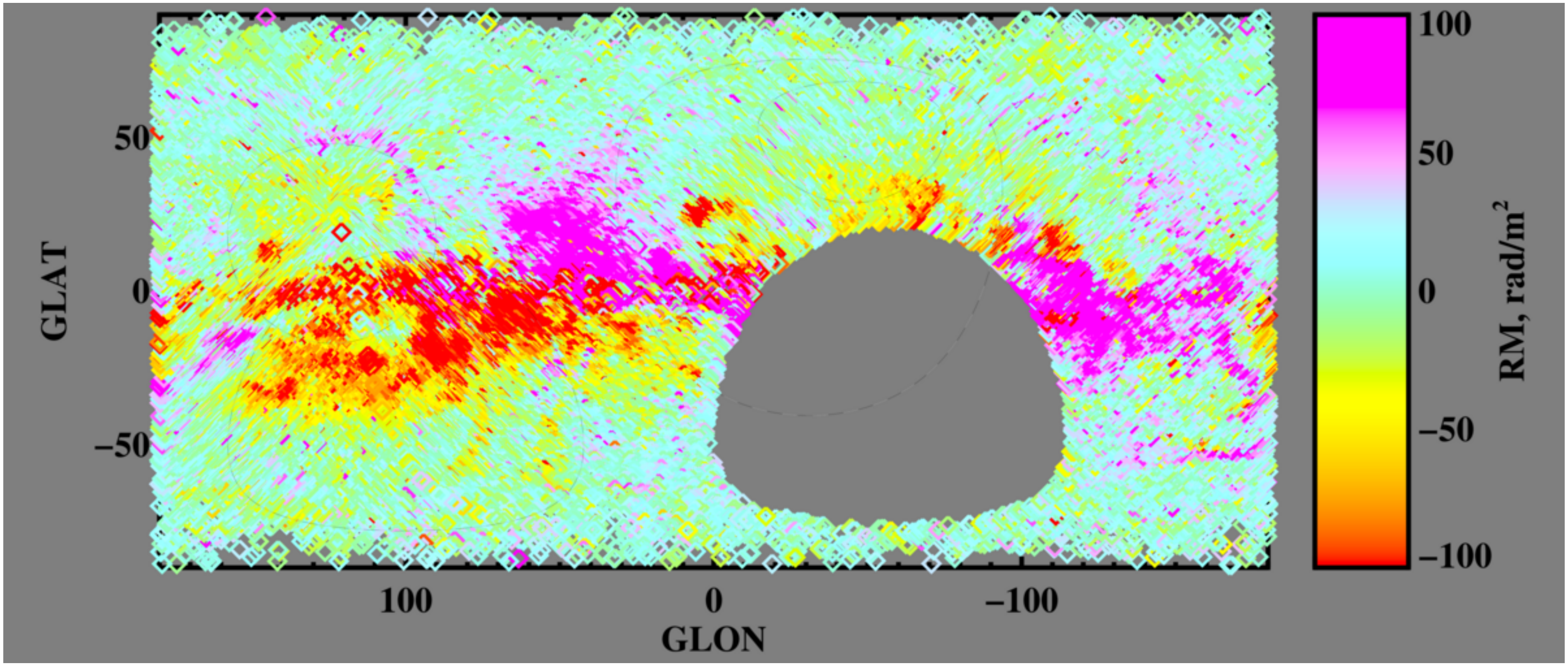
HI: 21-cm line (LAB)

Faraday RMs (Taylor, Stil, Sumsrum 2009)

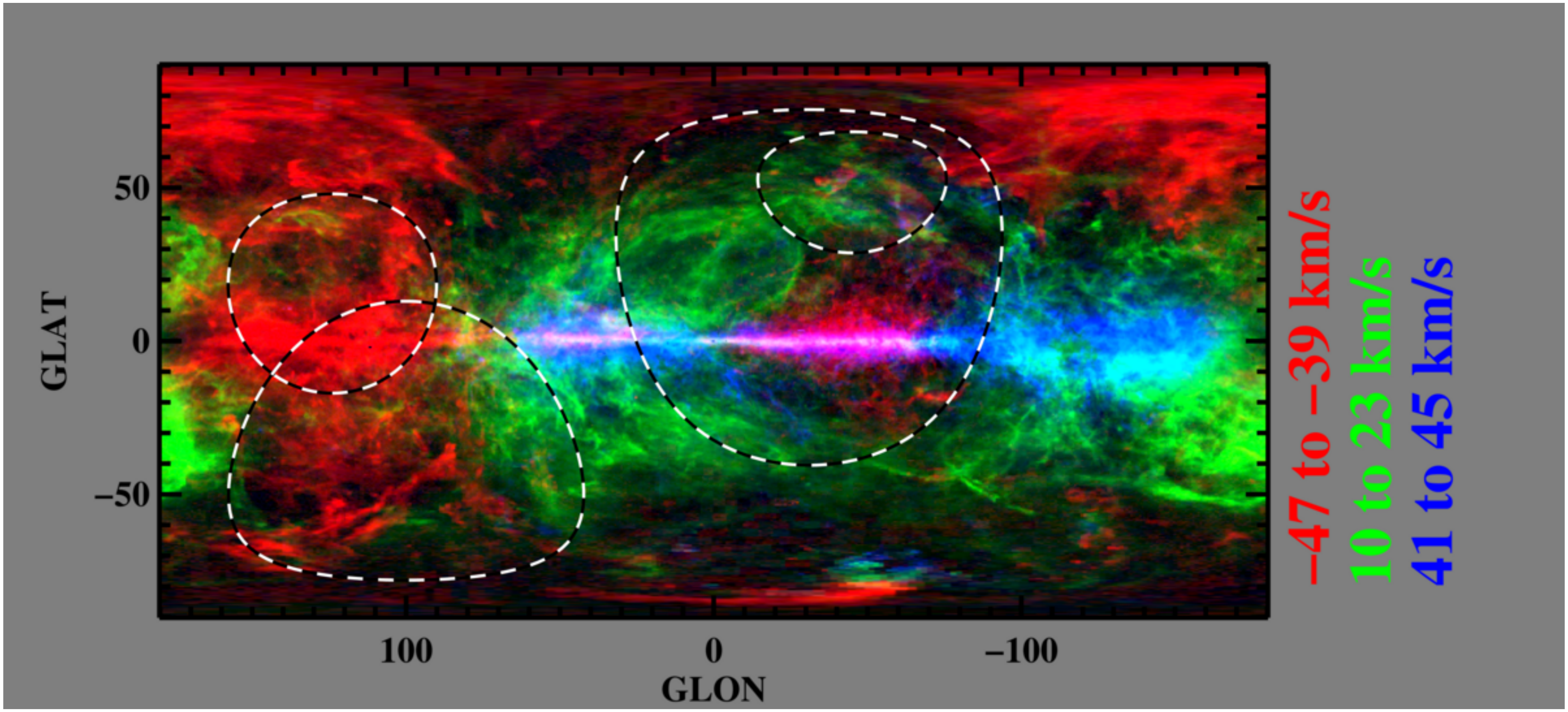
H+: H-alpha line (WHAM)




GLON
50
0
−50
GLAT
100
0
−100
GLON
3
4
1
2
0.5
0.4
0.3
0.2
0.1
0.0
Hα, Rayleighs



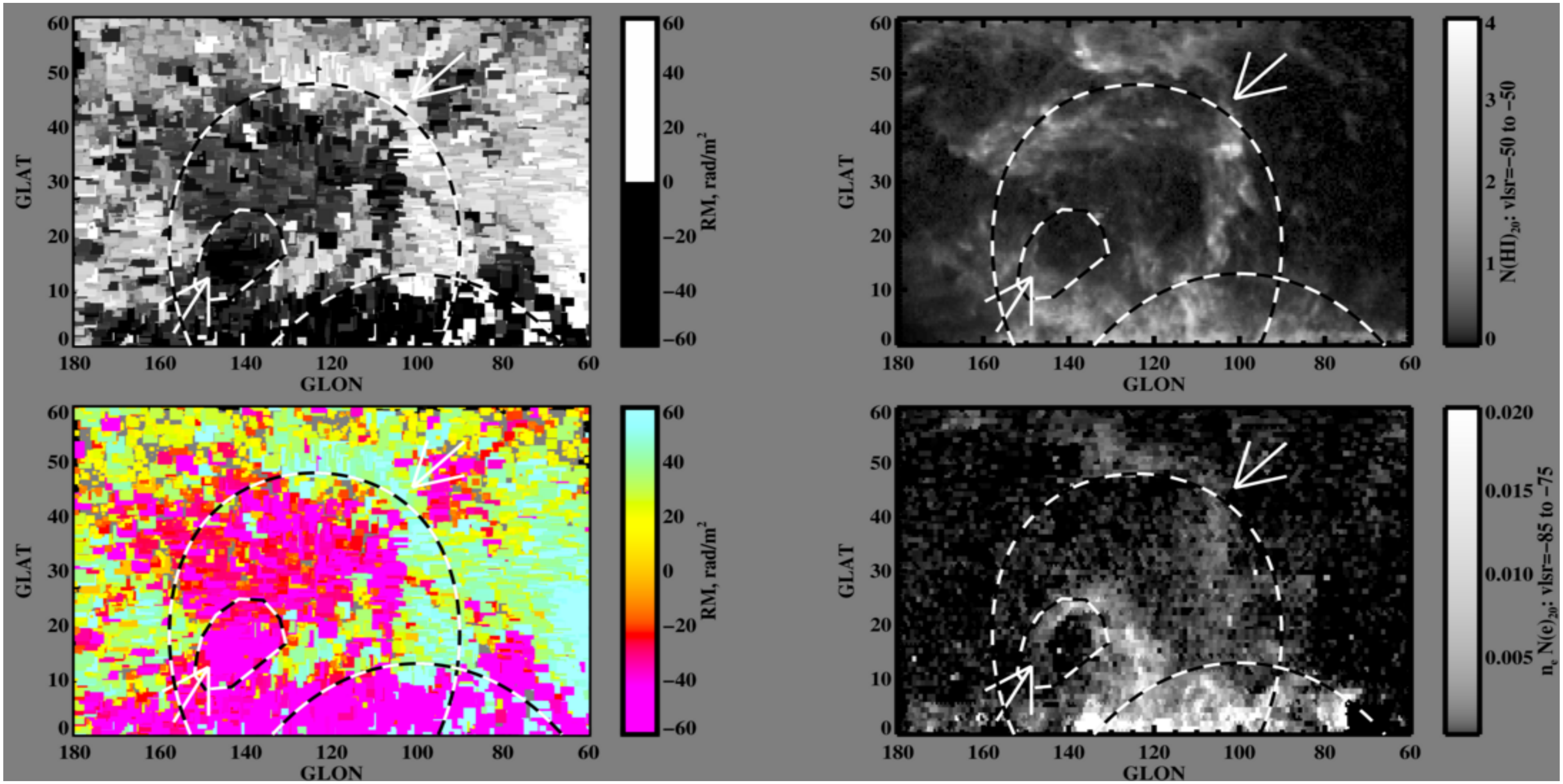
GLAT
50
0
−50
100
0
−100
GLON
100
50
0
−50
−100
RM, rad/m^2



GLAT
GLON
50
0
−50
100
0
−100
−47 to −39 km/s
10 to 23 km/s
41 to 45 km/s

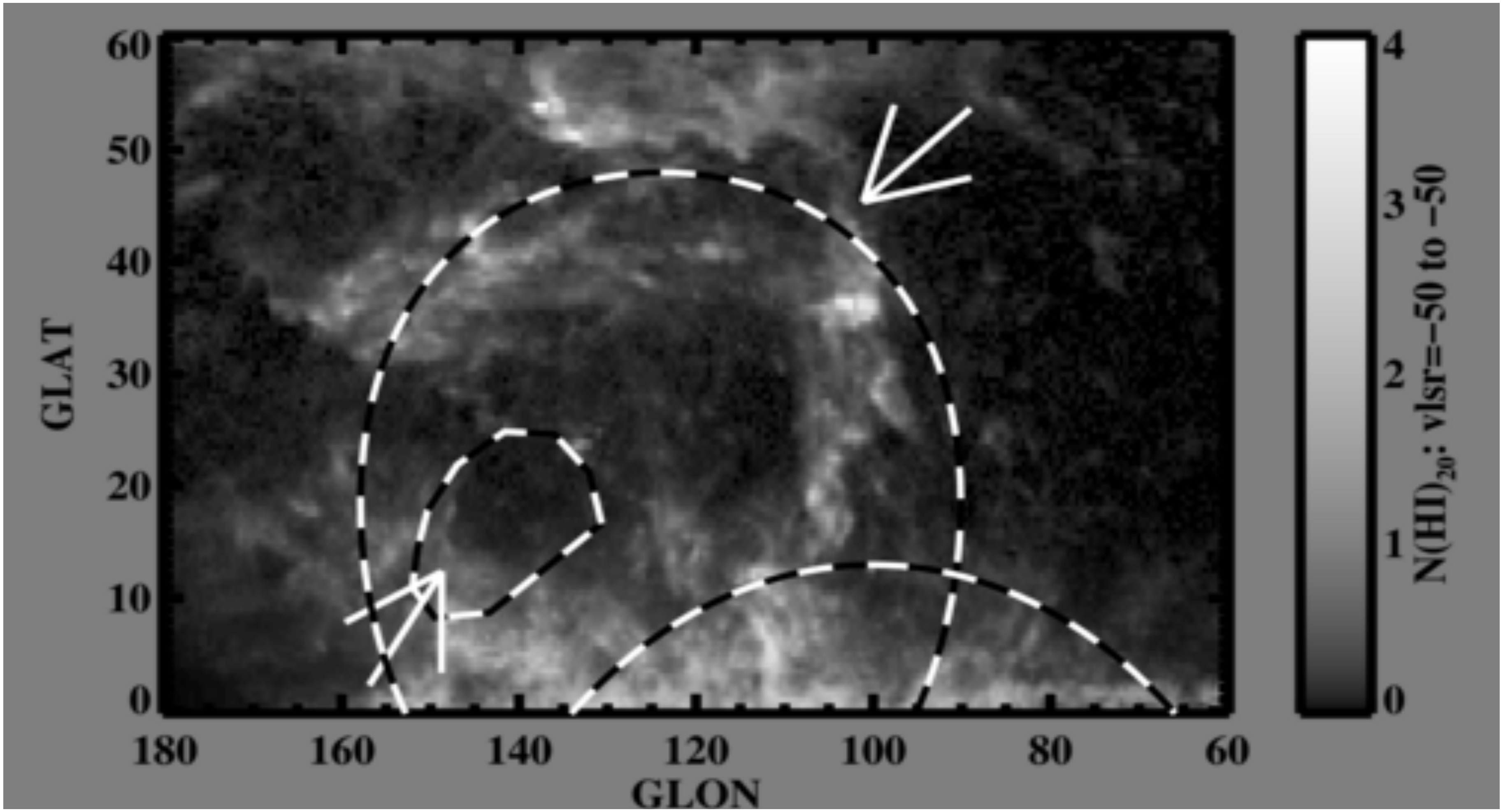
Let’s zoom in on the Radio Loop 3 vicinity…

RMs HI



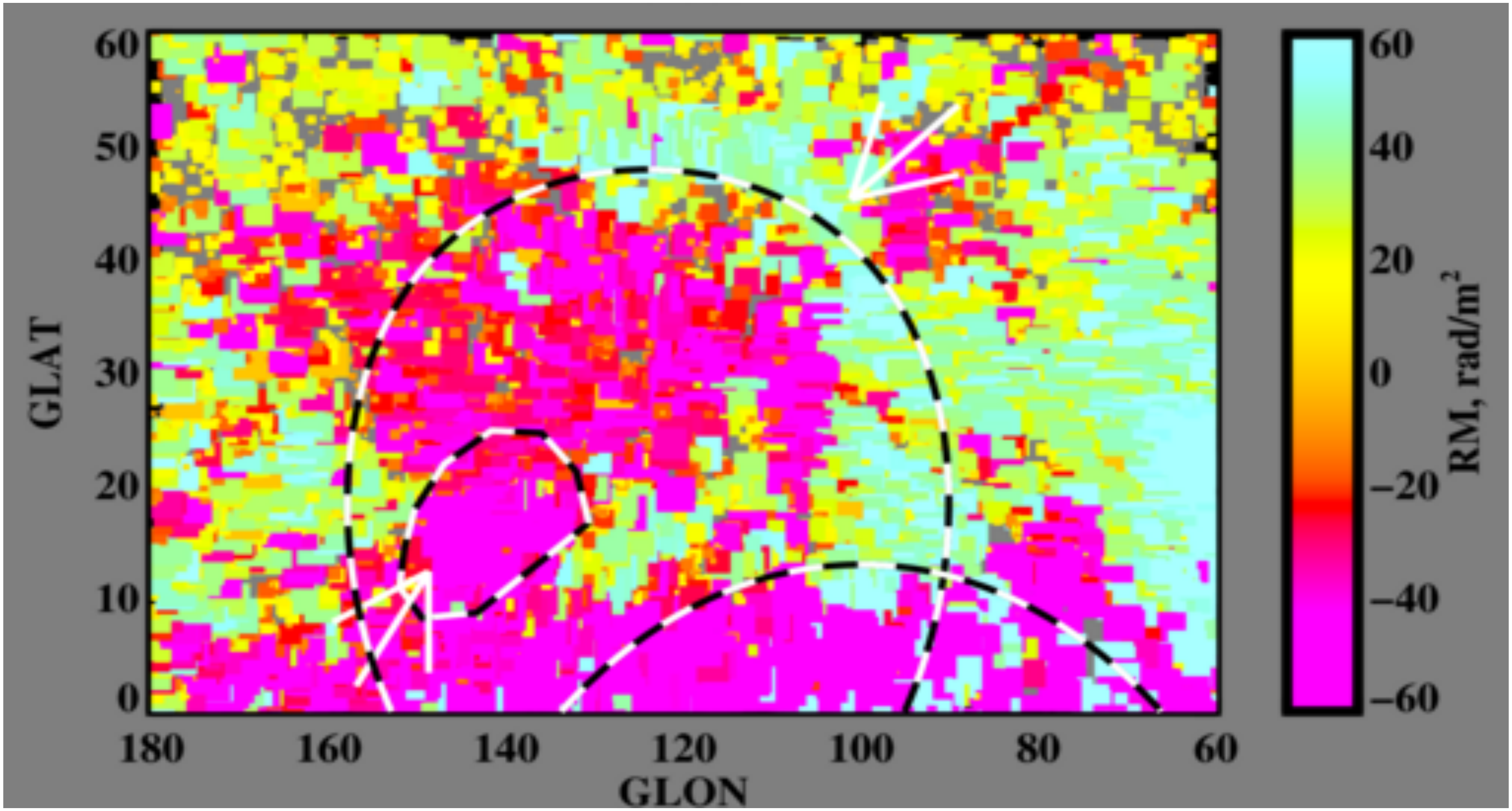
RMs H+

HI



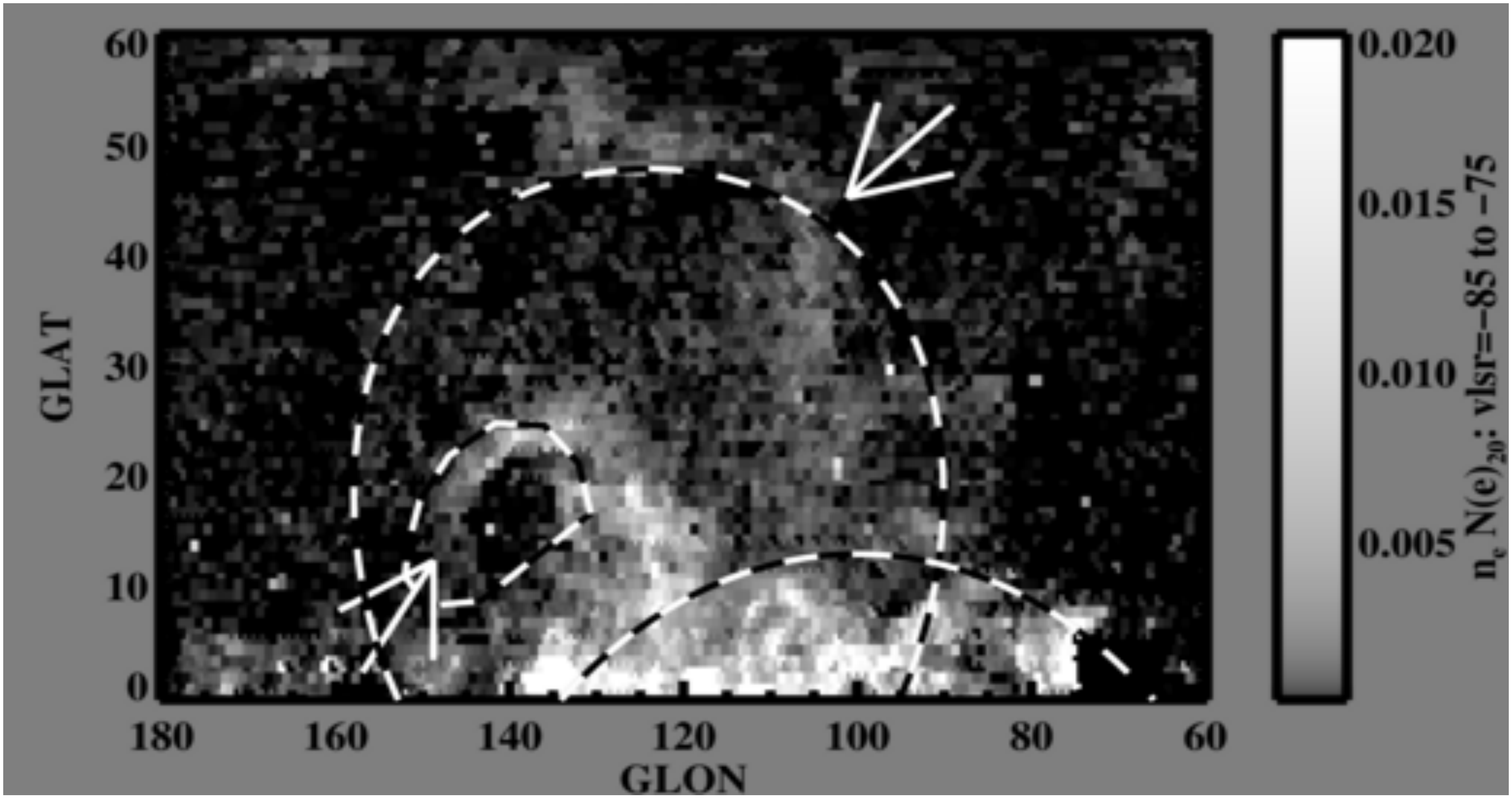
60
50
40
30
20
10
0
GLAT
180
160
140
120
100
80
60
GLON
4
3
2
1
0
N(HI)$_{20}$: vlsr=−50 to −50

HI



GLAT
60
50
40
30
20
10
0
180
160
140
120
100
80
60
GLON
60
40
20
0
−20
−40
−60
RM, rad/m^2

H+



GLAT
60
50
40
30
20
10
0
180
160
140
120
100
80
60
GLON
0.020
0.015
0.010
0.005
$n_e N(e)_{20}$: vlsr=−85 to −75

H+

Let's do some numbers…

$$RM = 0.81\ n_e B_{||} L \quad \text{rad m}^{-2}$$

We see ΔRM ~ 100 rad m^{-2}

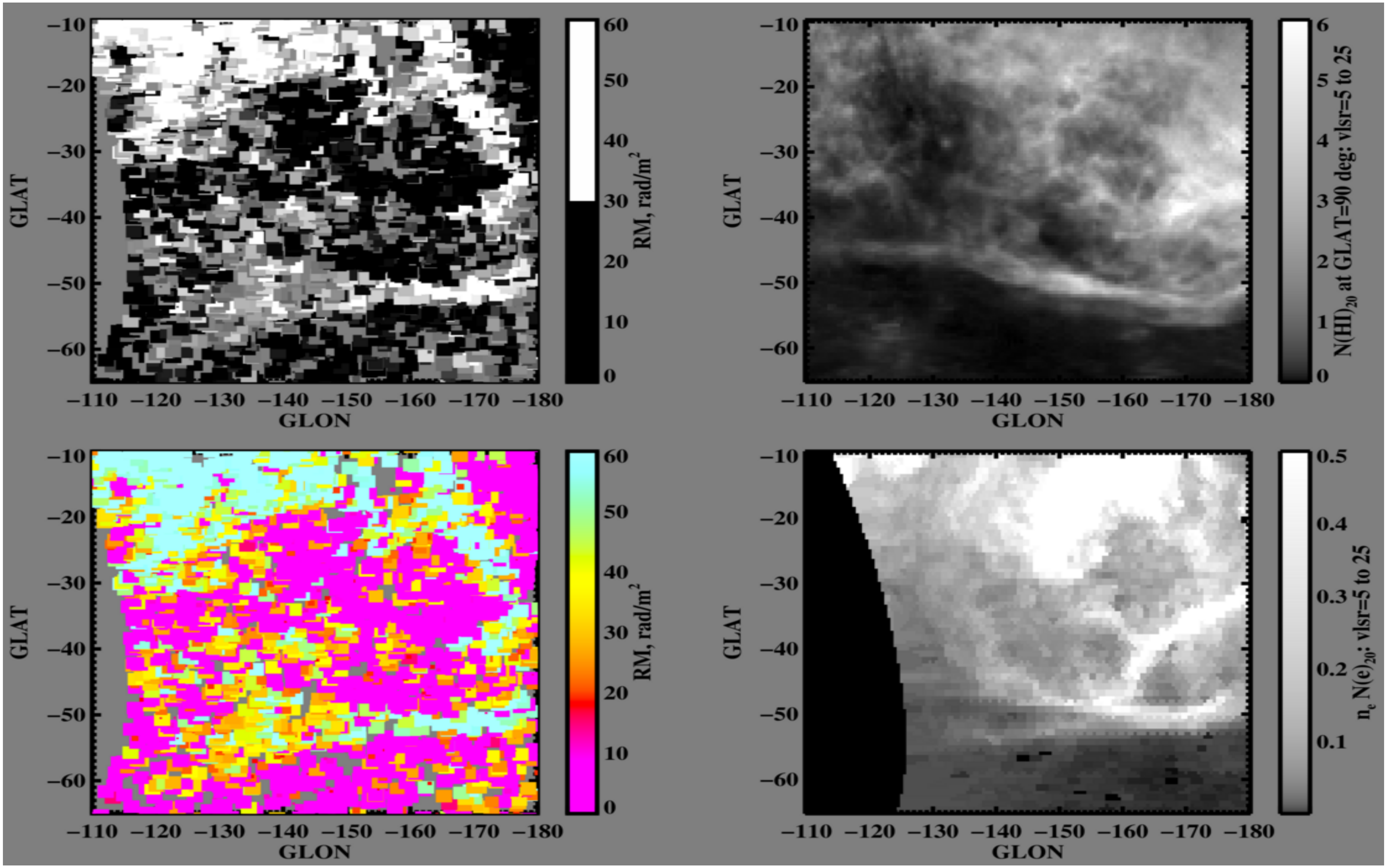
ΔEM ~ 2.0 cm^{-6} pc

If P_{WIM}~4000 cm^{-3} K, then n_e~0.5 cm^{-3} and $n_e L$~4 cm^{-3} pc, then

¡¡¡ B~30 μG !!!

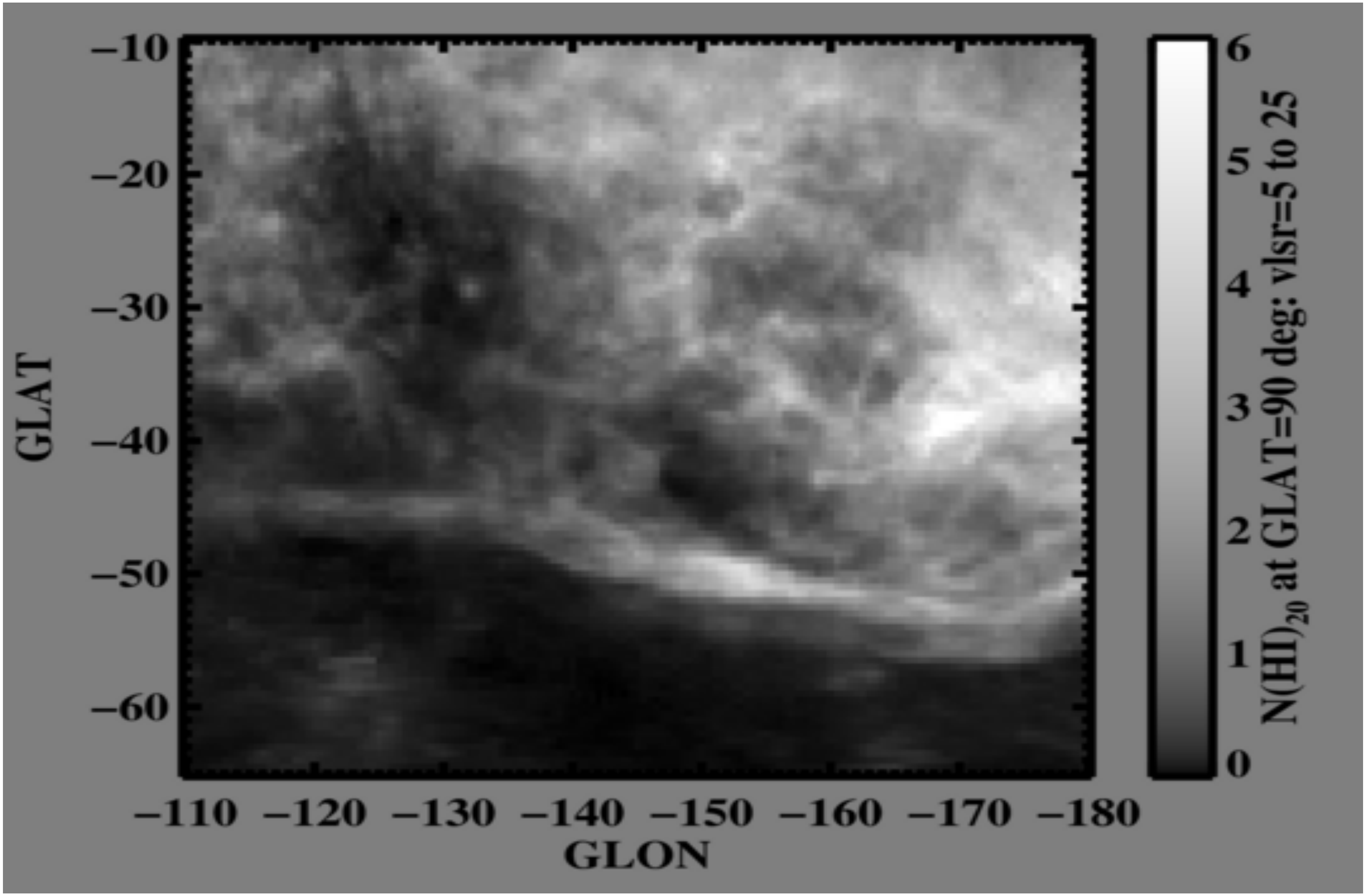
Now let’s zoom in on the Orion/Eridanus Superbubble…

RMs **HI**


GLAT
GLON
−110 −120 −130 −140 −150 −160 −170 −180
−10 −20 −30 −40 −50 −60
RM, rad/m^2
0 10 20 30 40 50 60
N(HI)$_{20}$ at GLAT=90 deg: vlsr=5 to 25
0 1 2 3 4 5 6
n_e N(e)$_{20}$; vlsr=5 to 25
0.1 0.2 0.3 0.4 0.5

RMs **H+**

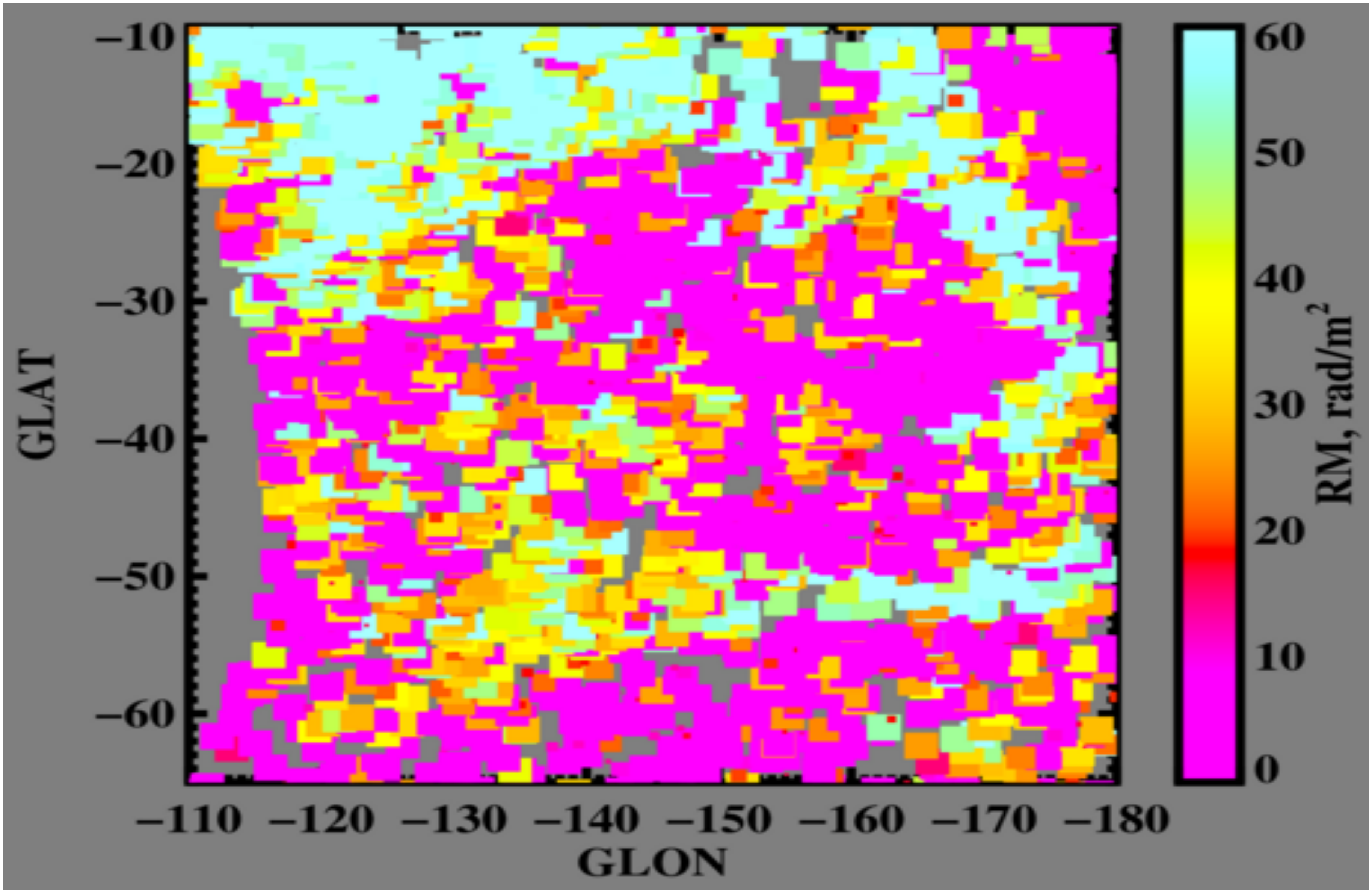
HI



GLAT
−10
−20
−30
−40
−50
−60
−110
−120
−130
−140
−150
−160
−170
−180
GLON
6
5
4
3
2
1
0
N(HI)20 at GLAT=90 deg: vlsr=5 to 25

HI

RM



−10
−20
−30
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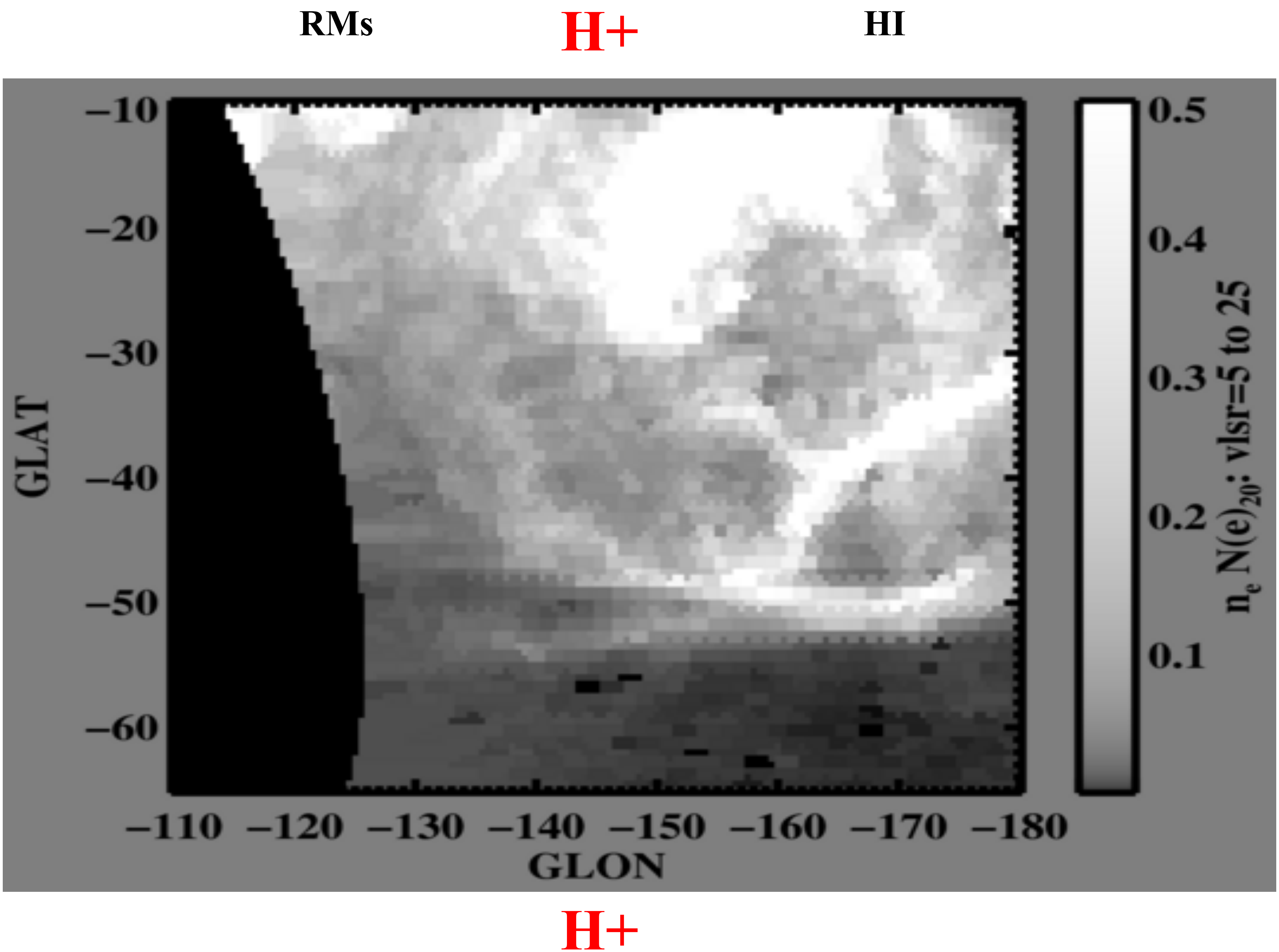
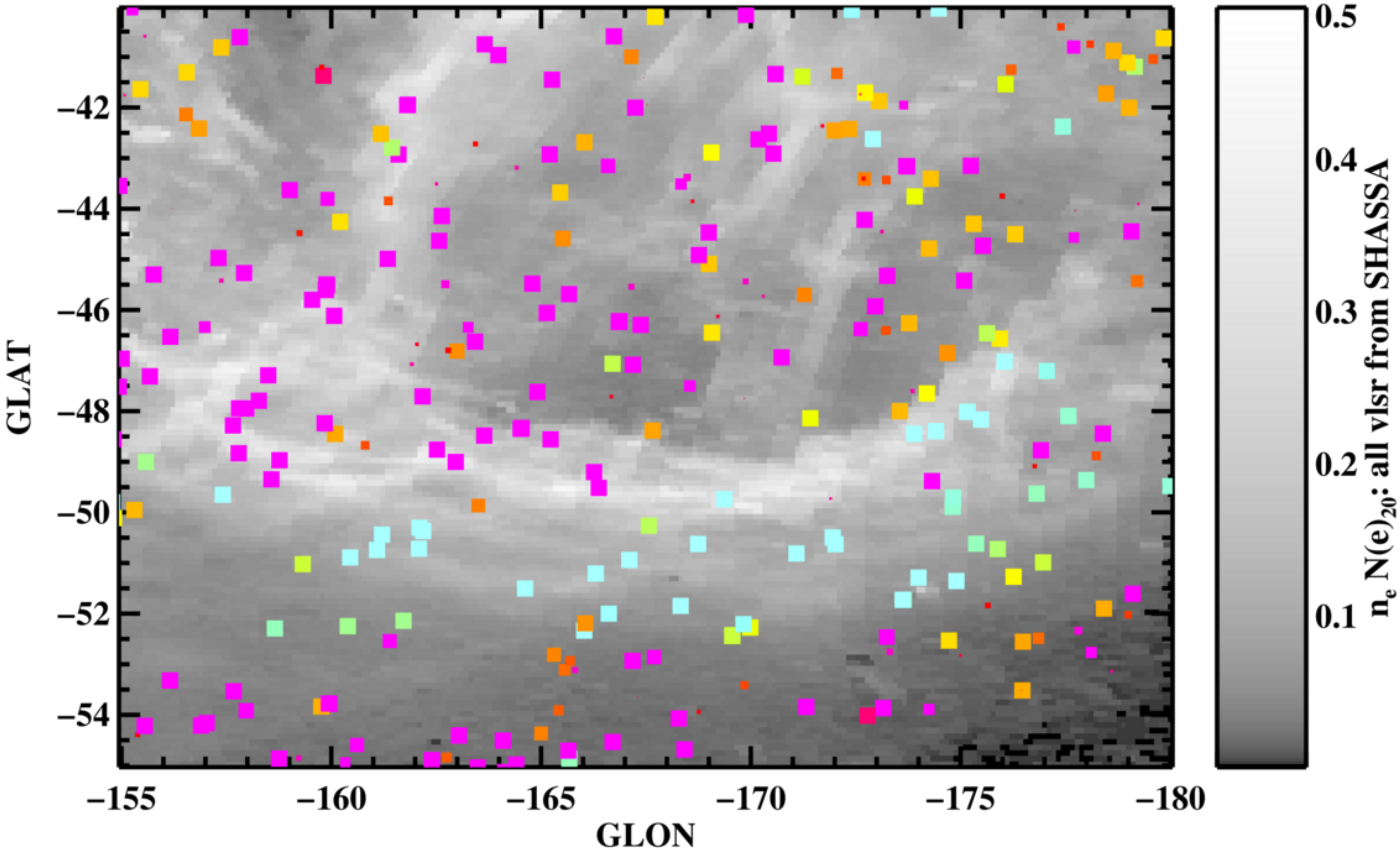
−50
−60
GLAT
−110
−120
−130
−140
−150
−160
−170
−180
GLON
60
50
40
30
20
10
0
RM, rad/m2

RM


RMs
H+
HI
GLAT
−10
−20
−30
−40
−50
−60
−110 −120 −130 −140 −150 −160 −170 −180
GLON
0.5
0.4
0.3
0.2
0.1
$n_e N(e)_{20}$: vlsr=5 to 25
H+



Higher angular resolution of H-alpha.

RMs are not well correlated with H-alpha line---i.e., the standard WIM.

Sensible conclusion: RMs are associated with large electron column, small emission measure—the WPIM.

<u>THIS IS THE FIFTH PHASE!</u>

best revealed by

<u>FARADAY ROTATION!</u>

We (or at least I; how about you?) believe that high-latitude RMs are dominated by INDIVIDUAL STRUCTURES— contrary to conventional viewpoint that they trace the GLOBAL GALACTIC FIELD.

A ROTATION MEASURE IMAGE OF THE SKY

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Received 2009 March 28; accepted 2009 July 20; published 2009 August 19

ABSTRACT

We have re-analyzed the NRAO VLA Sky Survey (NVSS) data to derive rotation measures (RMs) toward 37,543 polarized radio sources. The resulting catalog of RM values covers the sky area north of declination $-40°$ with an average density of more than one RM per square degree. We present an image of the median RM over 82% of the sky with a resolution of $8°$ and a typical error of ± 1–2 rad m^{-2}. The image shows large-scale structures in RM that extend to very high Galactic latitudes. A simple analysis of the RM structure at high Galactic latitudes is used to derive properties of the Galactic halo magnetic field in the solar neighborhood. We find the component of the local field perpendicular to the plane (the z-component) equal to $+0.30\ \mu$G for $z < 0$ and $-0.14\ \mu$G for $z > 0$. The reversal of sign across the Galactic plane is consistent with a quadrupole field geometry for the poloidal component of the halo field. The halo magnetic field component parallel to the disk is also found to be antisymmetric and generally consistent with a toroidal field, with strength $+0.83\ \mu$G for $z < 0$ and $-0.39\ \mu$G for $z > 0$. We have identified five regions of the sky where the foreground median RM is consistently less than 1 rad m^{-2} over several degrees. These holes in the foreground RM will be useful for future studies of possible small-scale fluctuations in cosmic magnetic field structures. In addition to allowing measurement of RMs toward polarized sources, the new analysis of the NVSS data removes the effects of bandwidth depolarization for $|\mathrm{RM}| \gtrsim 100$ rad m^{-2} inherent in the original NVSS source catalog. This new catalog of RMs and polarized flux densities is available online, and will be a valuable resource for further studies of the Galactic magnetic field and magnetoionic medium, and extragalactic magnetic fields.

Anti-symmetric RM sky: A0 dynamo!

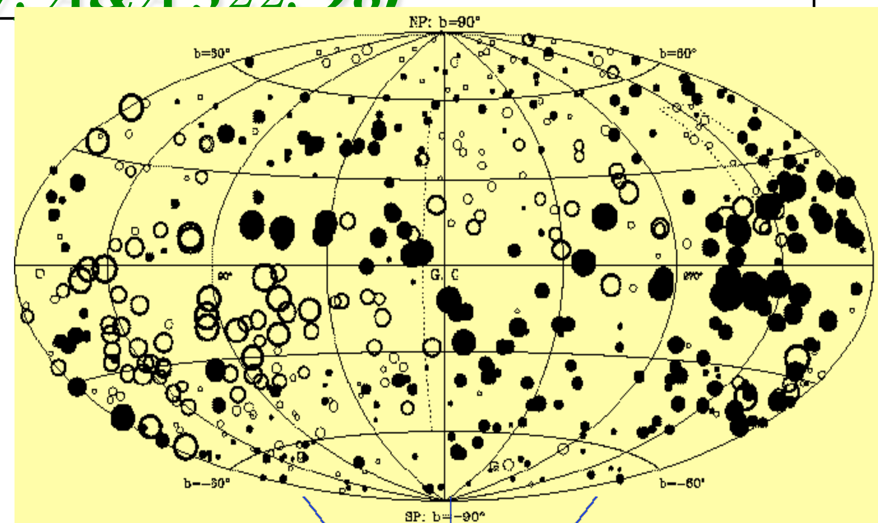
(Han et al. 1997, A&A 322, 98)

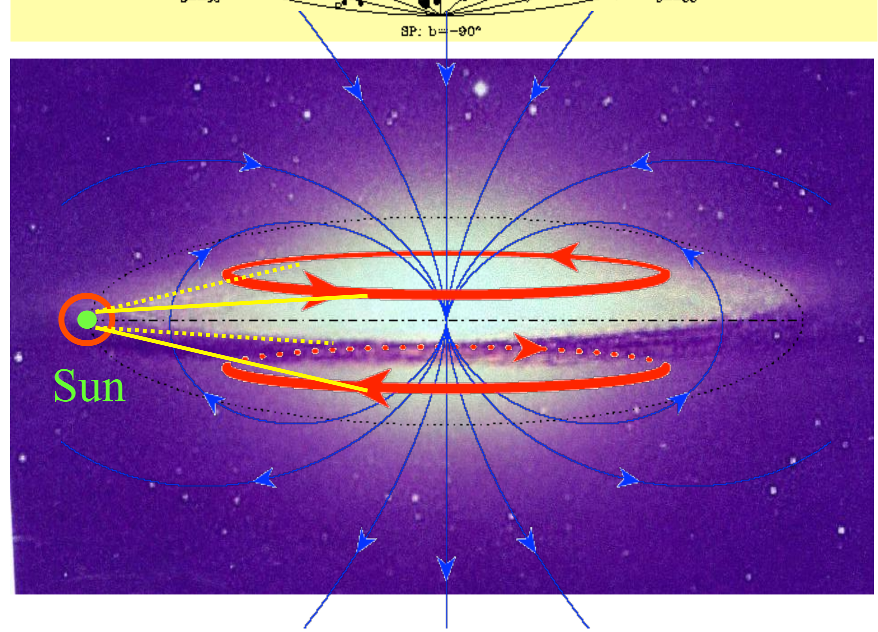
Evidence for global scale

- High anti-symmetry to the Galactic coordinates
- Only in inner Galaxy
- nearby pulsars show it at higher latitudes

Implications

- Consistent with field configuration of A0 dynamo
- The first dynamo mode identified on galactic scales





Given the dominance of individual structures in producing large RMs out of the plane, I don’t believe the “poloidal field” aspects of Global Galactic Field models.

However, the in-plane models are getting really good at matching the RM data!

MODELING THE MAGNETIC FIELD IN THE GALACTIC DISK USING NEW ROTATION MEASURE OBSERVATIONS FROM THE VERY LARGE ARRAY

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ABSTRACT

We have determined 194 Faraday rotation measures (RMs) of polarized extragalactic radio sources using new, multi-channel polarization observations at frequencies around 1.4 GHz from the Very Large Array (VLA) in the Galactic plane at $17° \leq l \leq 63°$ and $205° \leq l \leq 253°$. This catalog fills in gaps in the RM coverage of the Galactic plane between the Canadian Galactic Plane Survey and Southern Galactic Plane Survey. Using this catalog we have tested the validity of recently-proposed axisymmetric and bisymmetric models of the large-scale (or regular) Galactic magnetic field, and found that of the existing models we tested, an axisymmetric spiral model with reversals occurring in rings (as opposed to along spiral arms) best matched our observations. Building on this, we have performed our own modeling, using RMs from both extragalactic sources and pulsars. By developing independent models for the magnetic field in the outer and inner Galaxy, we conclude that in the inner Galaxy, the magnetic field closely follows the spiral arms, while in the outer Galaxy, the field is consistent with being purely azimuthal. Furthermore, the models contain no reversals in the outer Galaxy, and together seem to suggest the existence of a single reversed region that spirals out from the Galactic center.

Subject headings: Galaxy: structure — ISM: magnetic fields — polarization

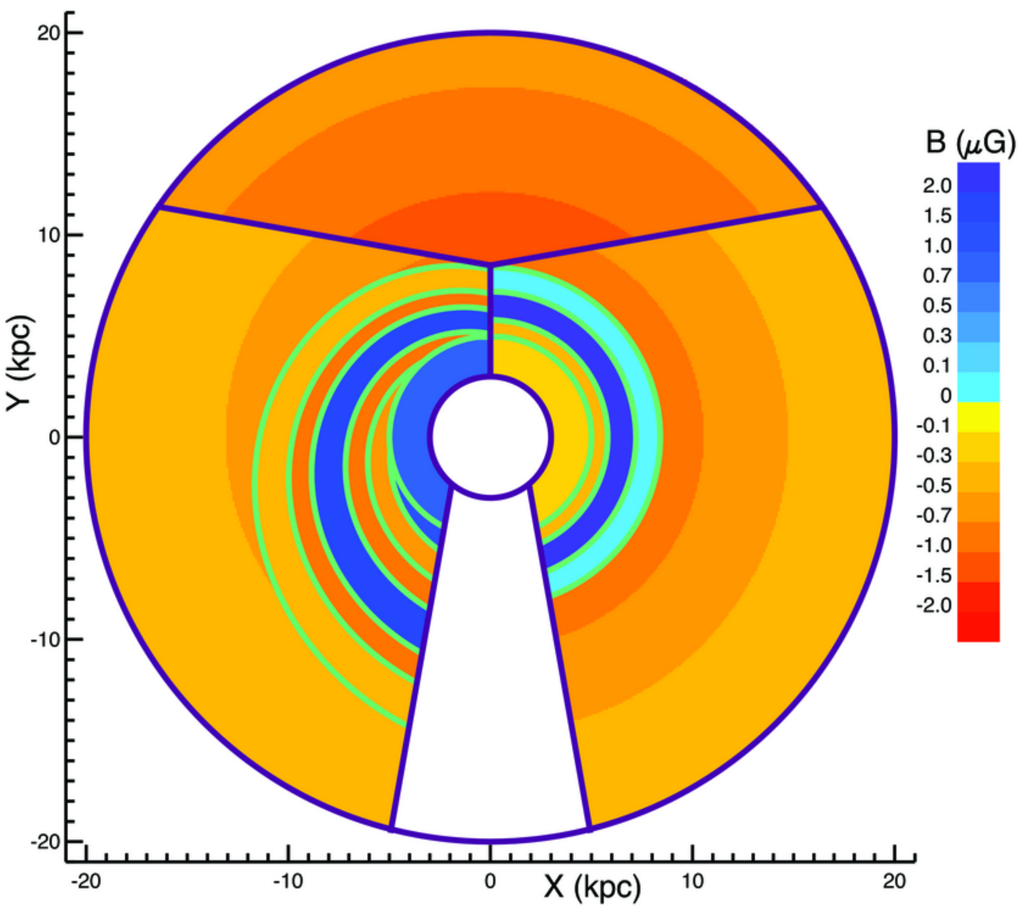
You probably missed that important highlight---print too small! The essence:

*** The <u>Inner-Galaxy</u> field has one reversal and the field follows the spiral arms**

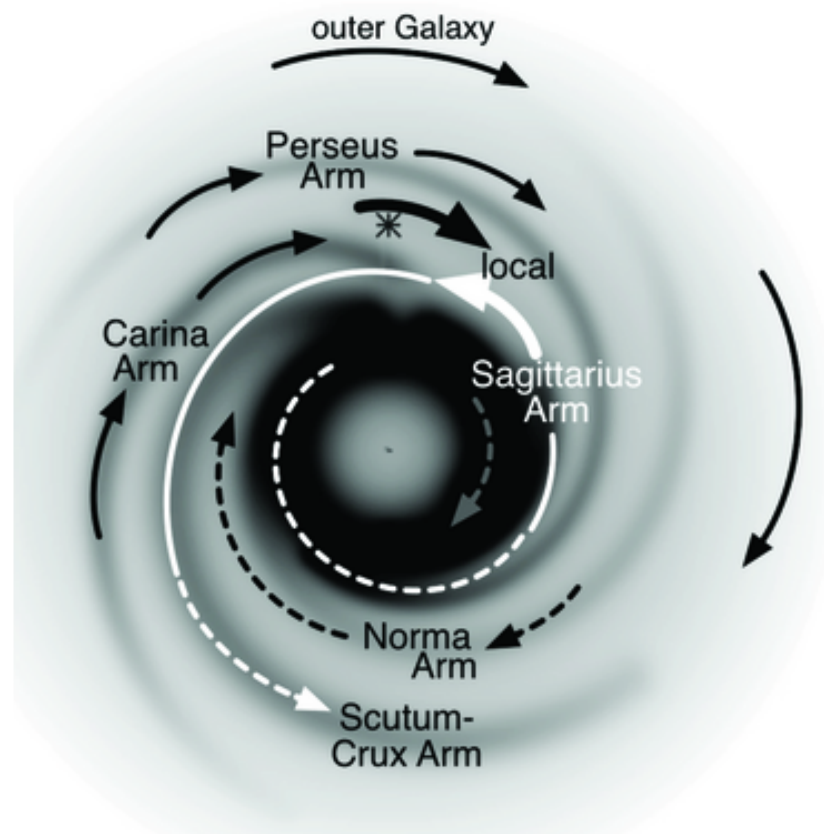
*** The <u>Outer-Galaxy</u> field has no reversals and follows circles**

Van Eck et al. (2011): My favorite Galactic-plane field model

Field Strength



Field Morphology



Near the Sun, field strengths and RMs are dominated by "fifth-phase" individual structures. Does this imply that b=0 RMs are also dominated by "fifth-phase" individual structures?

If so, it doesn't take many "fifth-phase" clumps to produce the observed b=0 RMs. If yes, the b=0 2 microG is not a valid number. Attacking this question directly requires lots of pulsar DMs, I think…

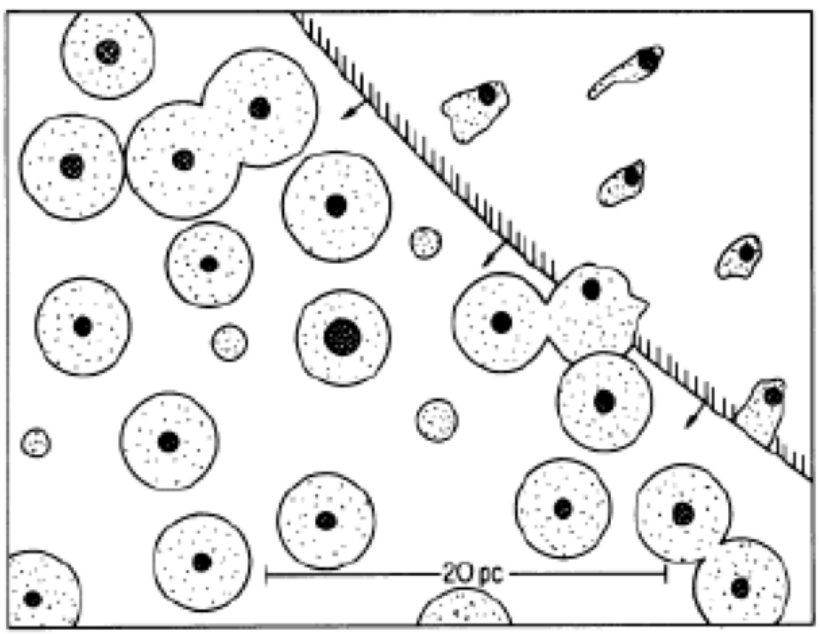
Fin

Fin

What do old SNRs look like?

GBT HI, NCP loop
(Robishaw 2007)

From McKee/Ostriker (1978), pictured in the most modern ISM textbook (Tielens 2005)



A CLOSE UP VIEW