Recent Observations

and

Interpretations

of the

Magnetic Field

in the

Milky Way

Jo-Anne Brown

Recent Observations

and

Interpretations

Stuff I have done...

in the

Milky Way

Jo-Anne Brown

Outline

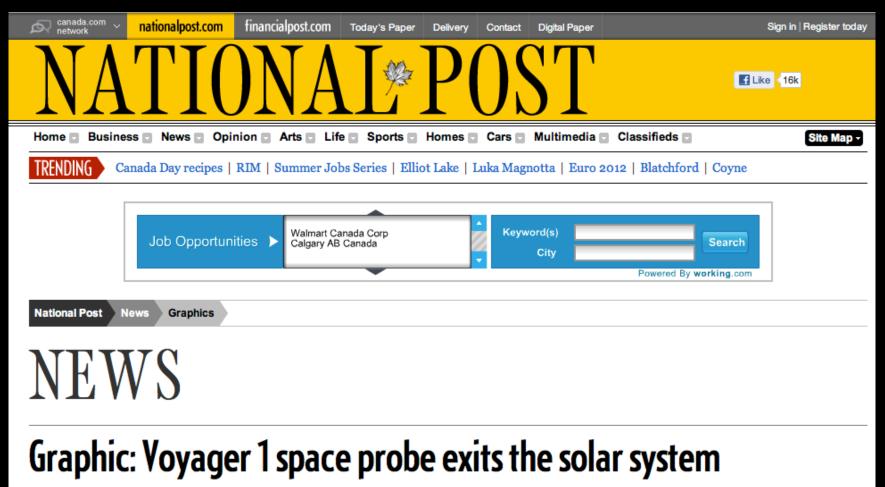- 'Recent' observations (CGPS, SGPS, VLA)

- Interpretations of the data

- Future directions

Constituents of Interstellar Medium

gas
- atomic
- molecular
- ionized

dust

cosmic rays

magnetic fields
do not radiate!

CGPS image

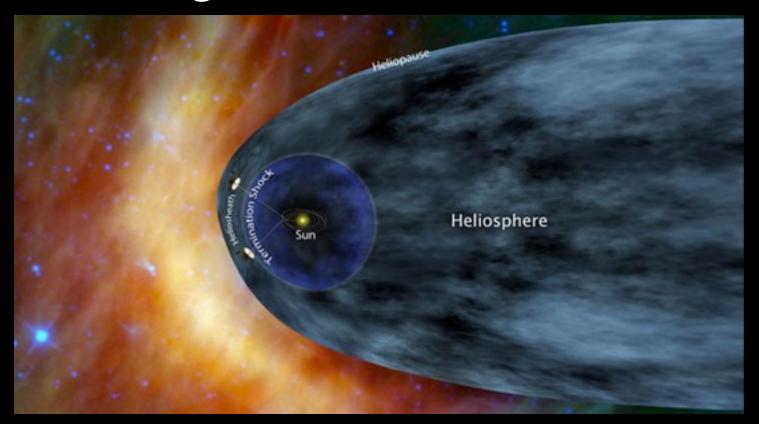Hubble image

RCW 86 (ESO/NASA image)

M51 (MPIfR image)

How?

June 22, 2012....

Measurements in the Solar System

NASA's Voyager 1+2
Launched: 1977
Mission objective:
Included measuring **B** for the Sun, Jupiter, Saturn, Uranus, Neptune, and the ISM.

In December 2004, V1 crossed the Termination Shock; V2 crossed it in August 2007...

Voyager Locations as of 2012

...35 years after launch, the probes are "almost" into the Interstellar Medium.

Considering the Scale Sizes…

11.2 billion km = 75 Au = 10 light-hours
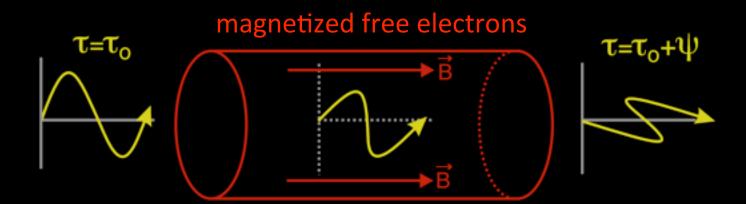

Solar system here

1.54×10^{18} km = 10.3 billion Au = 163,000 ly

Obviously,
we take a different approach!

Magnetic Field Measurement Techniques

- Faraday Rotation of *polarised* radiation
- Zeeman splitting
- *Polarisation* of infrared emission from dust grains
- *Polarisation* of starlight
- Synchrotron radiation intensity
- *Polarisation* of synchrotron radiation

Faraday Rotation

magnetized free electrons

$$\psi = \lambda^2 0.812 \int n_e \vec{B} \cdot \vec{dl}$$

$$= \lambda^2 \, RM$$

$$\tau = \tau_o + \lambda^2 \, RM$$
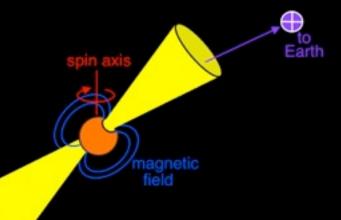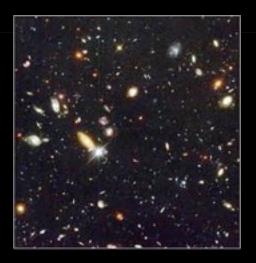
Sources of (predominately) Linear Polarisation

Pulsars

- Young neutron star with a strong B-field
- magnetic axis is misaligned with spin axis
- radiation emitted along magnetic axis is highly linearly polarised
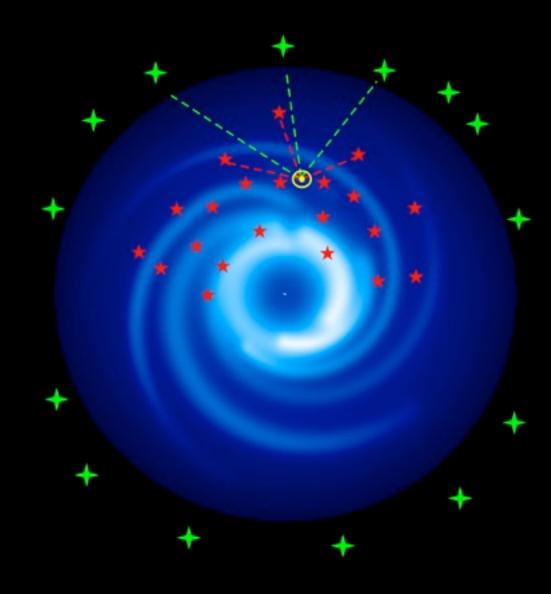
ExtraGalactic Sources (EGS)

- Contains an organized magnetic field
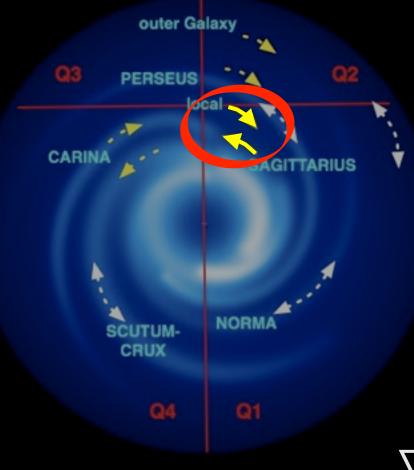- synchrotron radiation produces linearly polarised radiation

Comparing Pulsars to External Galaxies

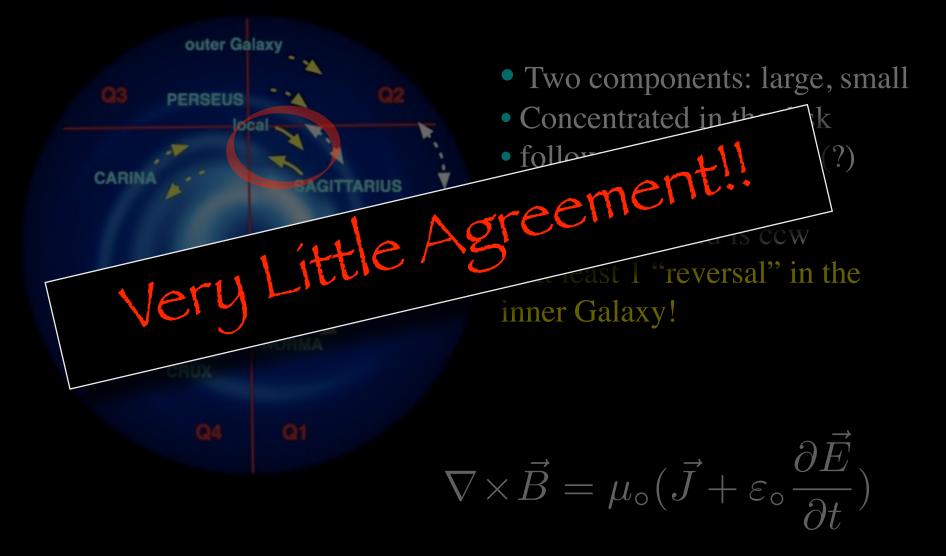Game: Who ever determines the most number (accurate) of RMs wins!

Galactic Magnetic Field Summary

- Two components: large, small
- Concentrated in the disk
- follows the spiral arms (?)
- local field is cw
- Sagittarius field is ccw
- At least 1 "reversal" in the inner Galaxy!

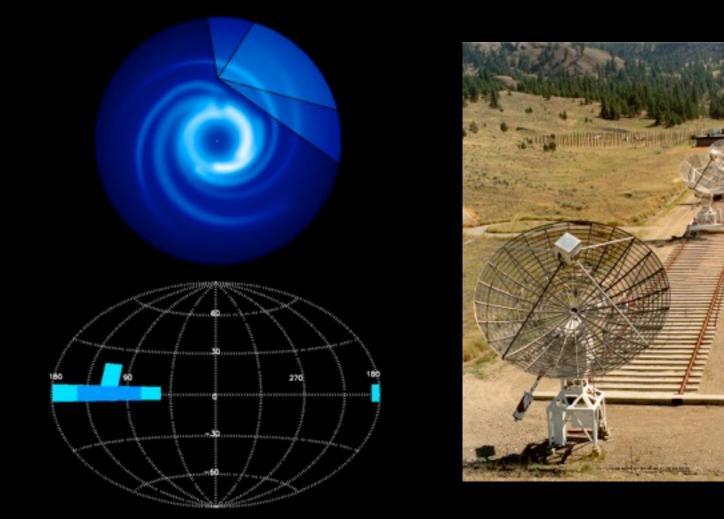$$\nabla \times \vec{B} = \mu_\circ (\vec{J} + \varepsilon_\circ \frac{\partial \vec{E}}{\partial t})$$
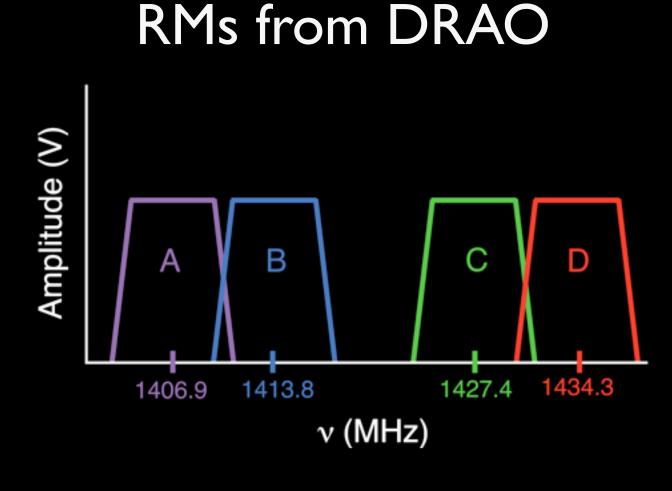
Galactic Magnetic Field Summary
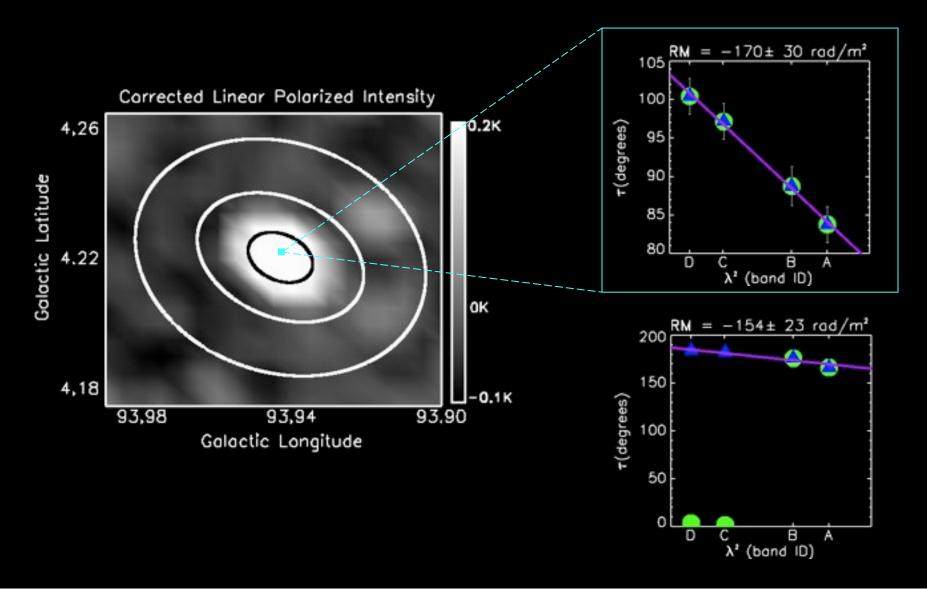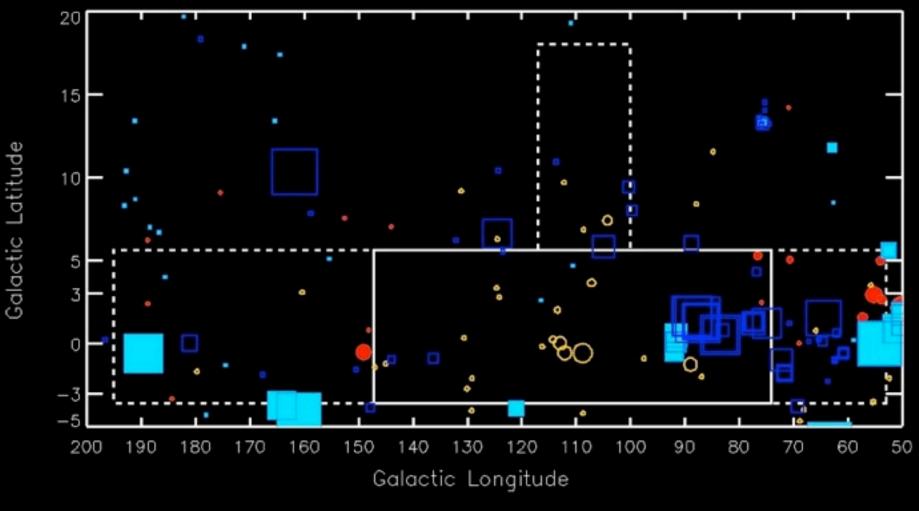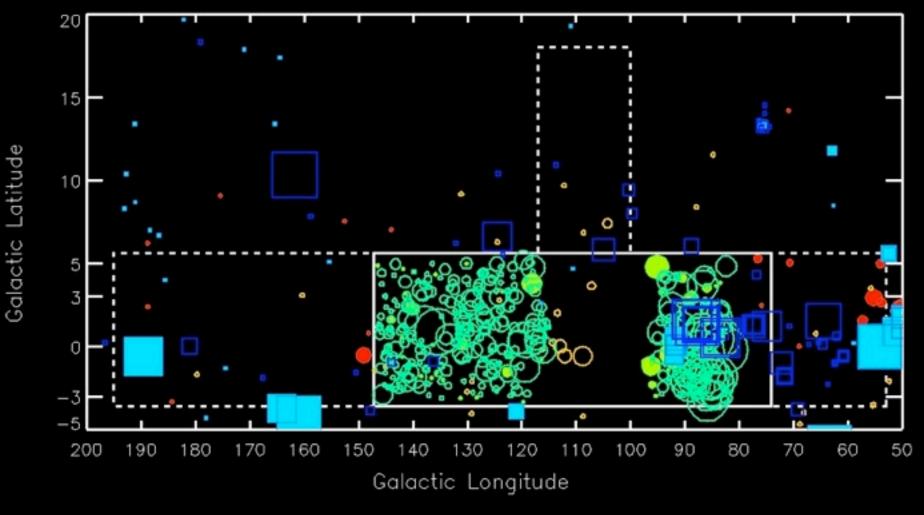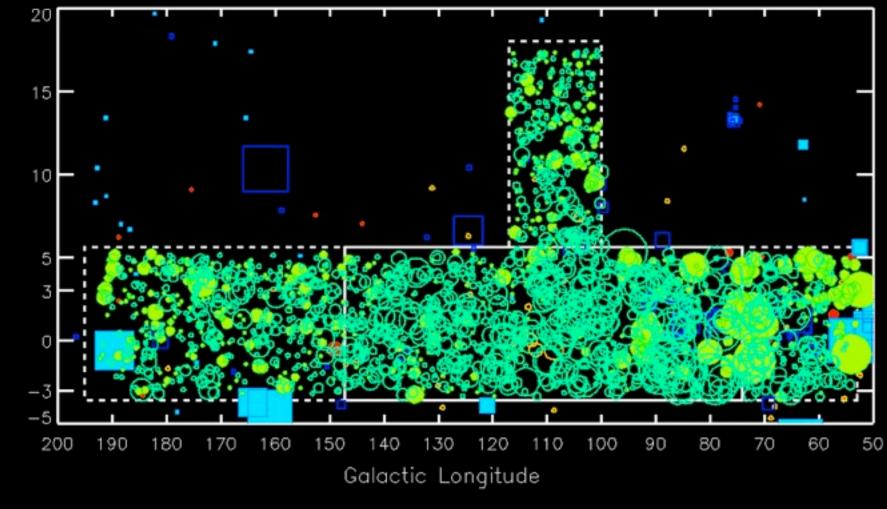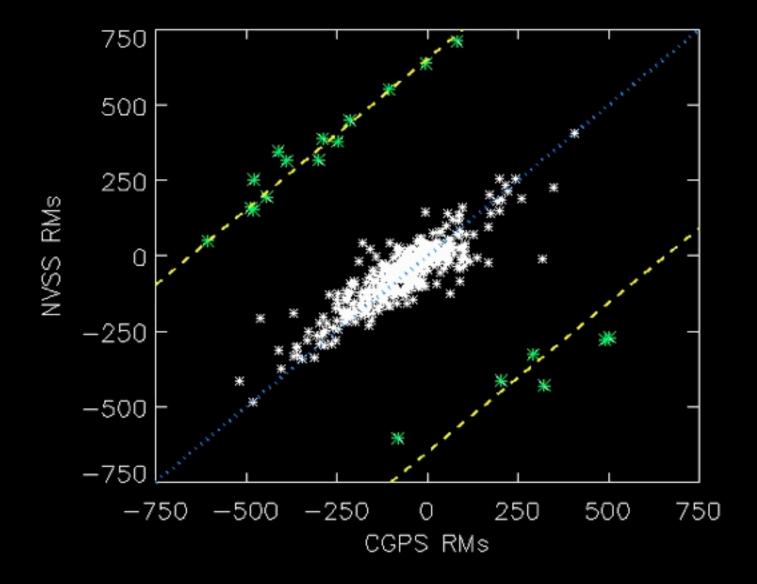
- Two components: large, small
- Concentrated in the ~~disk~~
- follow ~~~~ (?)
- ~~~~ is ccw
- ~~at least 1 "reversal" in the~~ inner Galaxy!

Very Little Agreement!!

$$\nabla \times \vec{B} = \mu_\circ(\vec{J} + \varepsilon_\circ \frac{\partial \vec{E}}{\partial t})$$

WARNING!

The material you are about to see is highly biased, though believed to be true.

Canadian Galactic Plane Survey

RMs from DRAO

$$\tau_i = \tau_o + \lambda_i^2 \, \text{RM} \quad \text{where } i = A, B, C, D$$

Sample Calculation

RM Sources in the CGPS…

Published as of 2001: 27 pulsars, 40 EGS

…with the first publication…

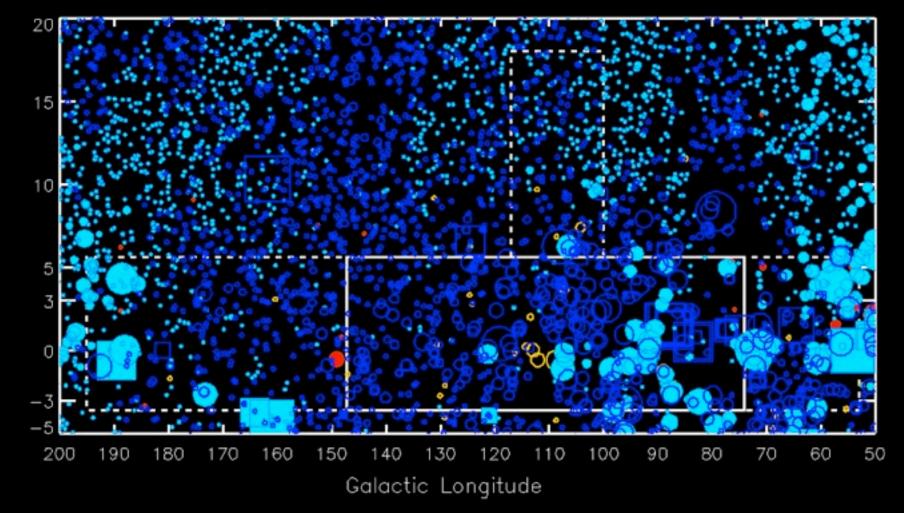380 RM sources in the CGPS phase I

…with the latest data (2012).
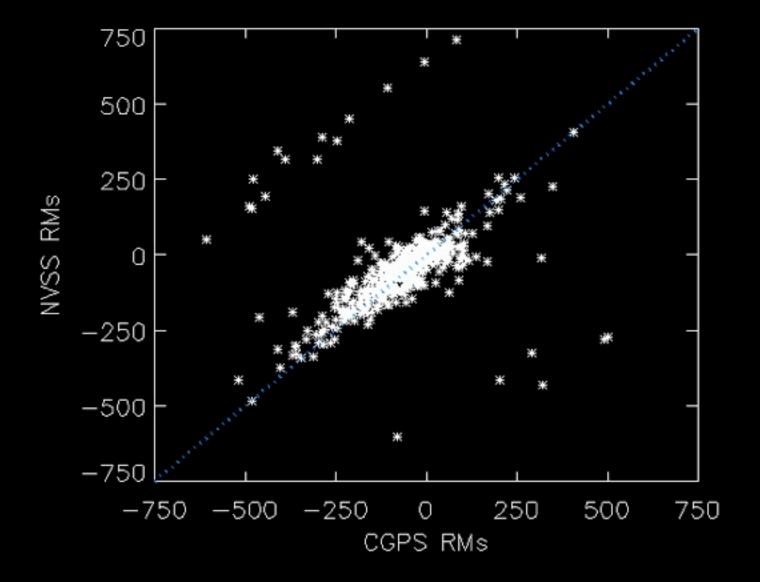

>1500 new RM sources in the CGPS region!

NVSS RM data in the same area:

Comparison of CGPS with NVSS

Comparison of CGPS with NVSS

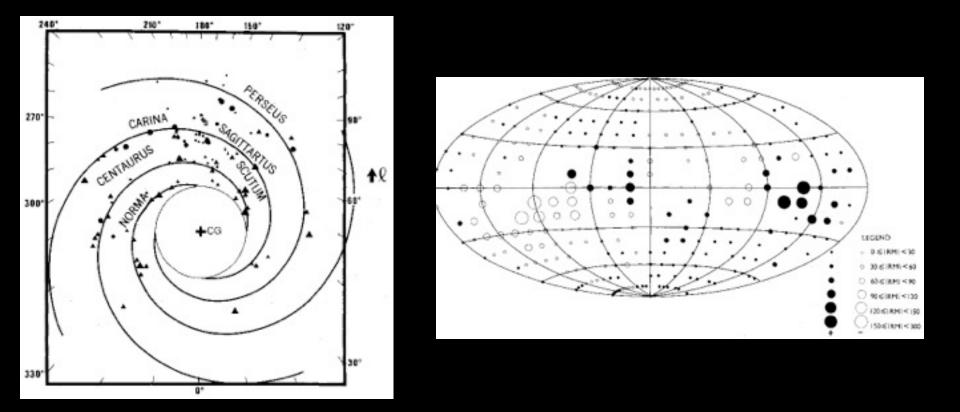# BE CAREFUL
with the
NVSS
(especially near the disk)

Top 4 Contributions of the CGPS

1. No Reversals in the Outer Galaxy

2. Locating the RM 'null' in the Outer Galaxy

3. Examination of the scale-height of RM

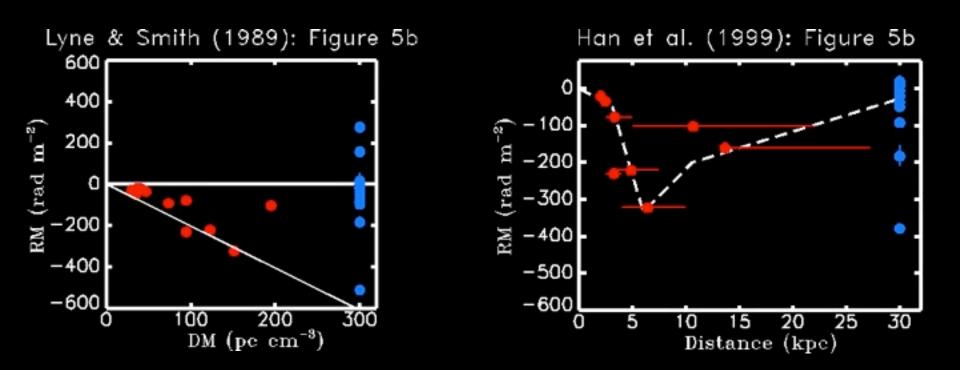4. Modeling disk-GMF using pulsars and EGS

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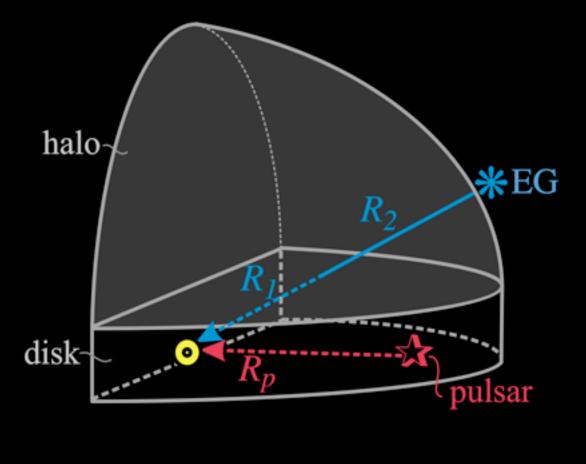4. Modeling disk-GMF using pulsars and EGS

Reversals in the Outer Galaxy

Simard-Normandin & Kronberg (1980)
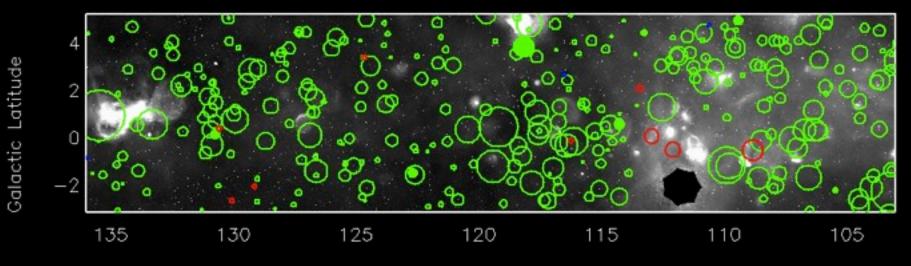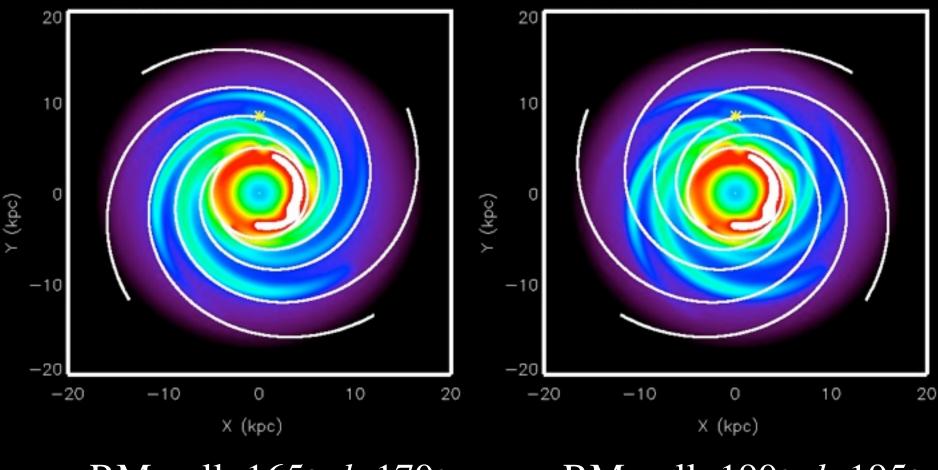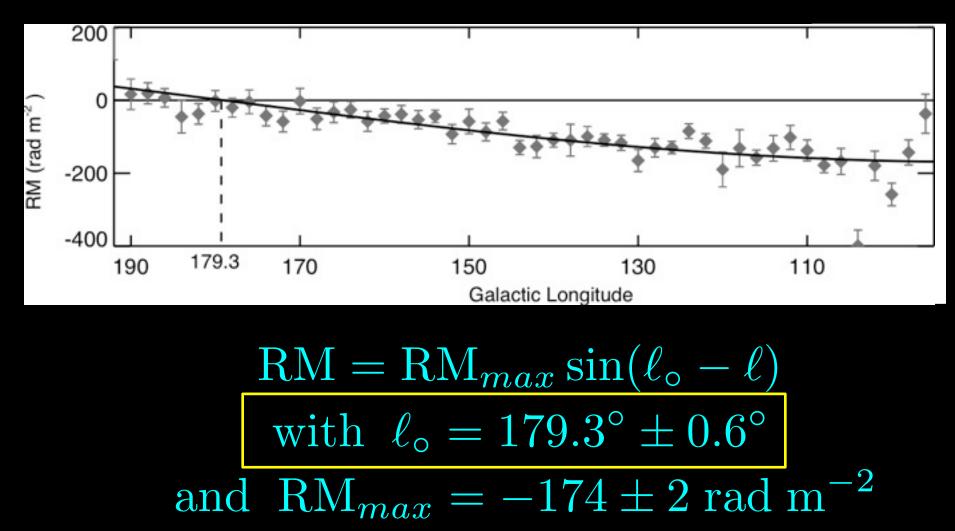determined no reversals in the outer Galaxy.

Reversals in the Outer Galaxy

Lyne & Smith (1989): Figure 5b

Han et al. (1999): Figure 5b

Data ranges: Lyne & Smith (1989):$105^{\circ} < l < 135^{\circ}$, $|b| < 30^{\circ}$
Han et al. (1999): $104^{\circ} < l < 119^{\circ}$, $|b| < 30^{\circ}$

Path Length Comparison

halo

*EG

R_2

R_1

disk

R_p

pulsar

$R_1 < R_p$

CGPS for $105^{\circ} < l < 135^{\circ}$

Combining Pulsars with CGPS EGS:

1) No detectable magnetic field reversal in the outer Galaxy.
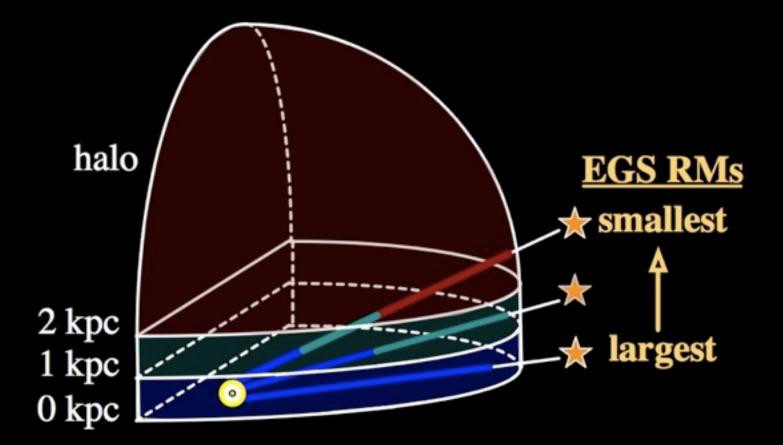
2) ne, B decay as 1/R in the outer Galaxy.

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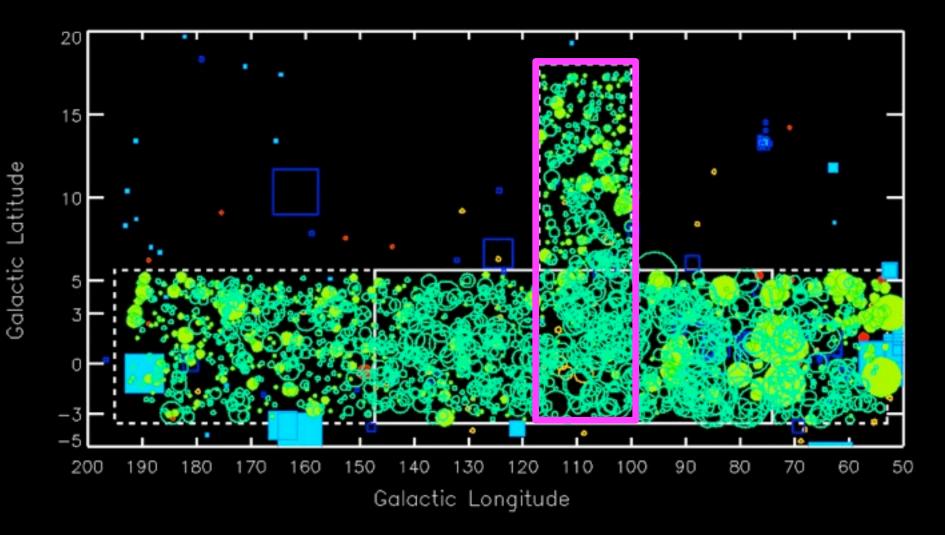
4. Modeling disk-GMF using pulsars and EGS

Predicted RM Null

RM null: $165^{\circ} < l < 170^{\circ}$

RM null: $l \sim 180^{\circ}$

What if the Null is at *l* > 180º?

RM null: 165º<*l*<170º

RM null: 190º<*l*<195º

Observed RM Null

$$\mathrm{RM} = \mathrm{RM}_{max} \sin(\ell_\circ - \ell)$$

$$\text{with } \ell_\circ = 179.3° \pm 0.6°$$

$$\text{and } \mathrm{RM}_{max} = -174 \pm 2 \text{ rad m}^{-2}$$

Rae and Brown (2011)

Top 4 Contributions of the CGPS

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Rotation Measure

~~Magnetic~~ Field Scale Height

$$\mathrm{RM} = 0.812 \int n_e \, \mathbf{B} \cdot \mathrm{d}\mathbf{l}$$

Need to know (un-, anti-)correlation of B with n_e!

RM Scale Height

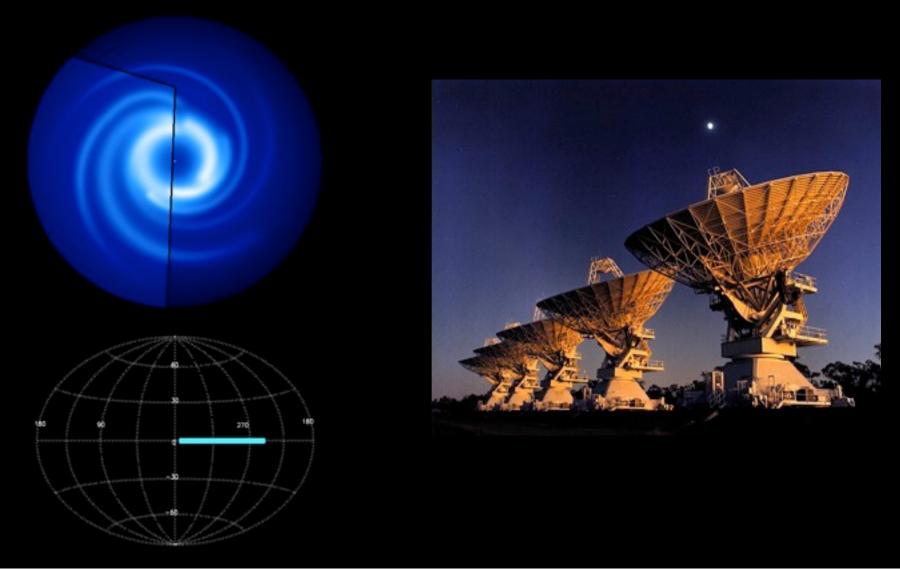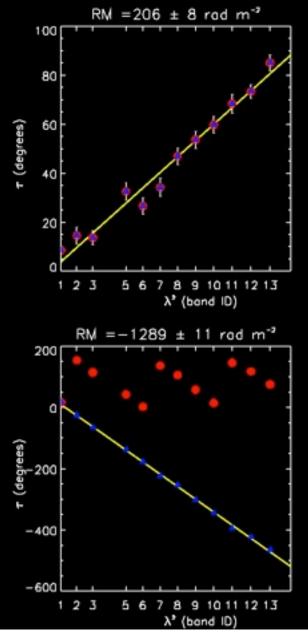# Using the high-latitude CGPS:

Rae & Brown 2011
(Naramata Proceedings)

$$\mathrm{RM} = \mathrm{RM_\circ} \exp(x^2/2) \text{ with } x = \frac{b - b_\circ}{\sigma}$$

Rae & Brown 2011
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$$\mathrm{RM} = \mathrm{RM}_\circ \exp(x^2/2) \text{ with } x = \frac{b - b_\circ}{\sigma}$$

Using CGPS-2012 data

Using NVSS data (as is)

Using NVSS matched with CGPS

Using CGPS-2012 data

RM Scale Height

RM Scale Height

109°

8.5 kpc

8.0 kpc

15 kpc

6.36°

90°

1.10 kpc

1.15 kpc

Top 4 Contributions of the CGPS

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Top ~~4~~ 5 Contributions of the CGPS

1. No Reversals in the Outer Galaxy

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4. Modeling disk-GMF using pulsars and EGS

5. **Lead the way for an 'industry' of EGS RMs!**

Southern Galactic Plane Survey

Southern Galactic Plane Survey

RM sources in the SGPS…

Published as of 2006: 120 pulsars, 1 EGS...

…with new EG sources.

…published *July 2007*: 120 pulsars, 149 EGS

SGPS Results:

Model Distribution of B

1) Field is CW everywhere except in the Scutum-Crux arm and molecular ring.

2) Field is aligned with the arms (particularly in the inner Galaxy).

Brown et al. (2007)
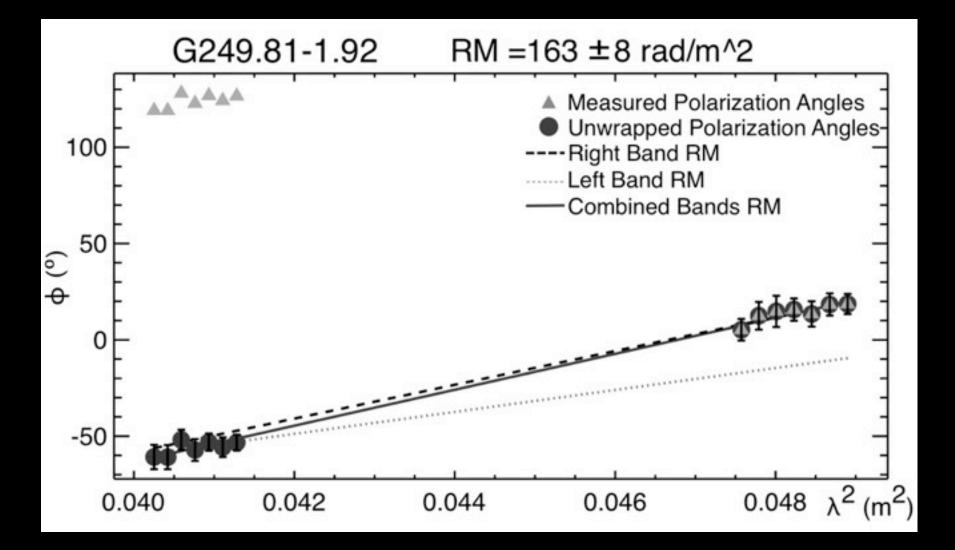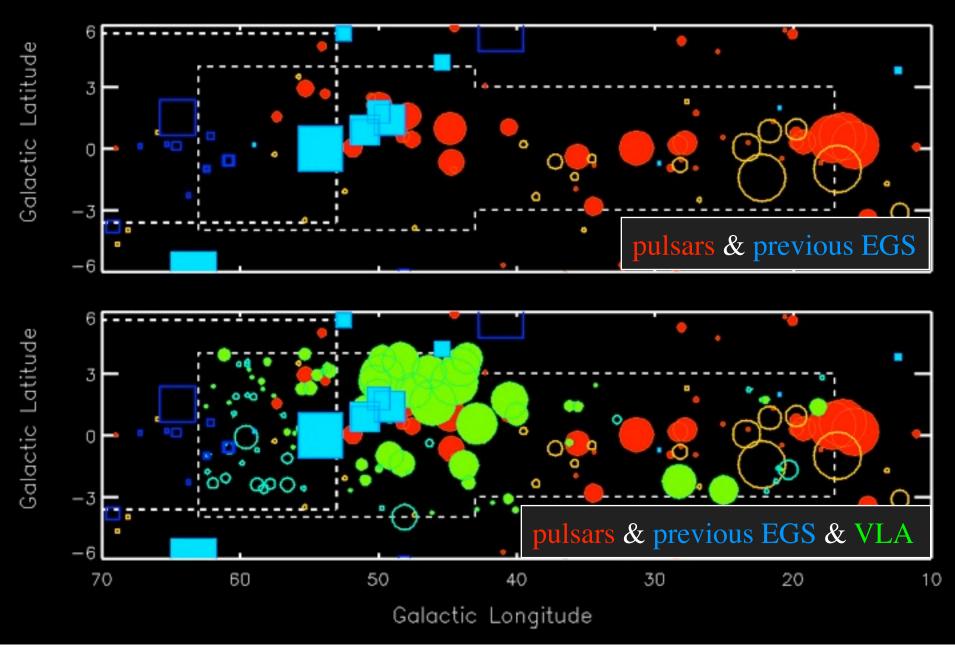
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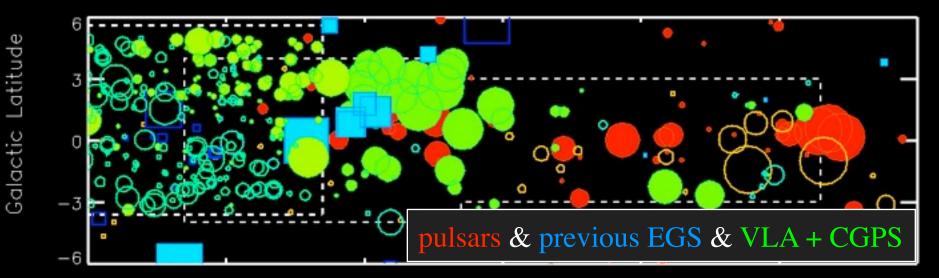Brown et al. (2007)
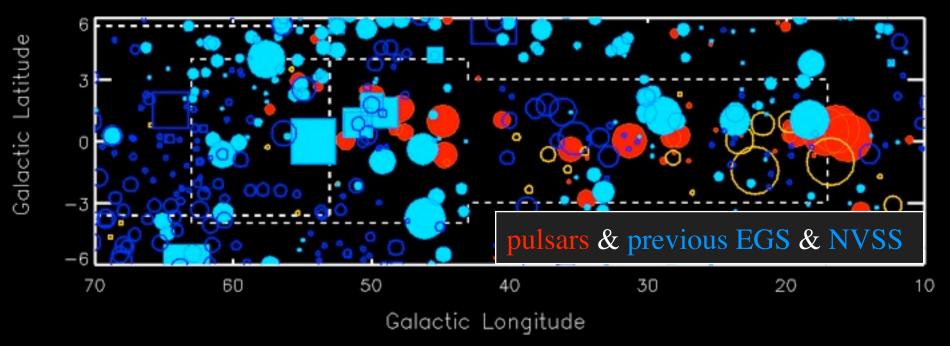
VLA Observations

VLA Observations

VLA Observations

G249.81-1.92   RM =163 ±8 rad/m^2

VLA Observations - Q1

pulsars & previous EGS

pulsars & previous EGS & VLA

Tuesday, 10 July, 12

VLA Observations - Q1

pulsars & previous EGS & VLA + CGPS

pulsars & previous EGS & NVSS

VLA Observations - Q3

pulsars & previous EGS

pulsars & previous EGS & VLA

VLA Observations - Q3

pulsars & previous EGS & NVSS

pulsars & previous EGS & VLA

Comparison with NVSS

VLA Observations - High Latitude

VLA Observations - High Latitude
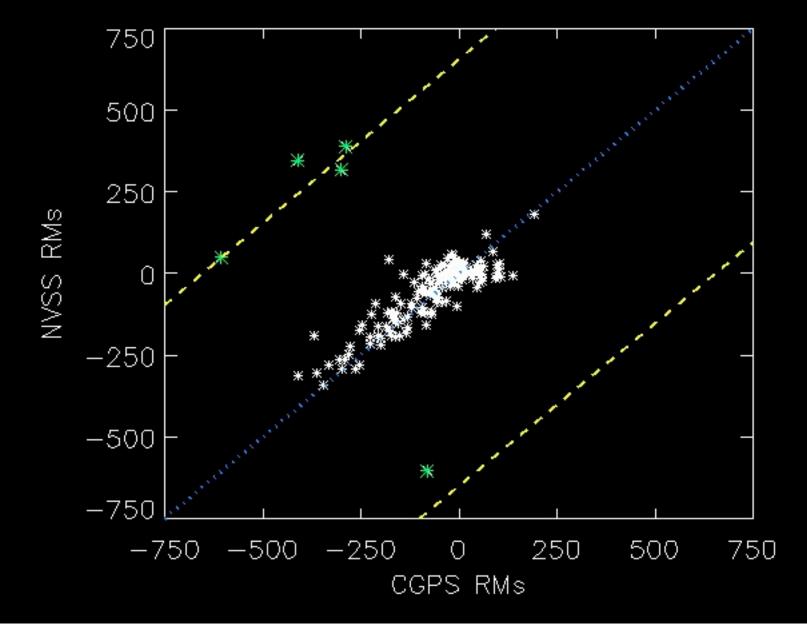
pulsars & previous EGS & VLA + CGPS

pulsars & previous EGS & NVSS

Comparison of Mao et al. with NVSS
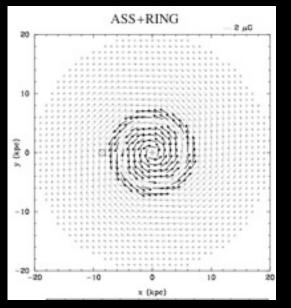
Comparison of NLE-CGPS with NVSS

Top 3 Contributions of the VLA Observations

1. Differentiating between the 'Sun' models

2. ID of symmetry across the disk

3. New model of the GMF

Top 3 Contributions of the VLA Observations
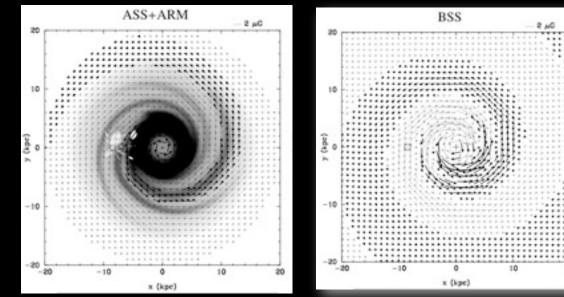
1. Differentiating between the 'Sun' models

2. ID of symmetry across the disk

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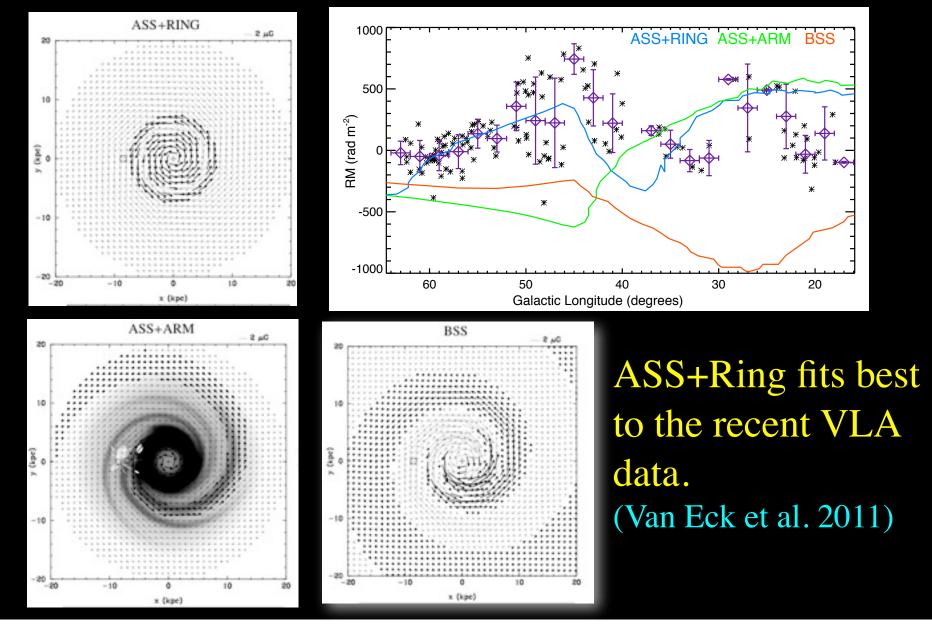
Recent Models: Sun et al. (2008)

Model fields are spiral, but with different reversal boundaries (i.e. ring or spiral).

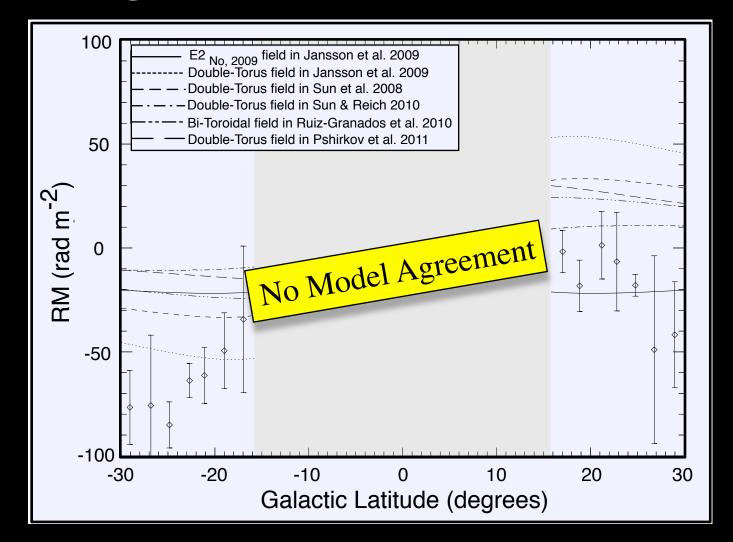# Recent Models: Sun et al. (2008)

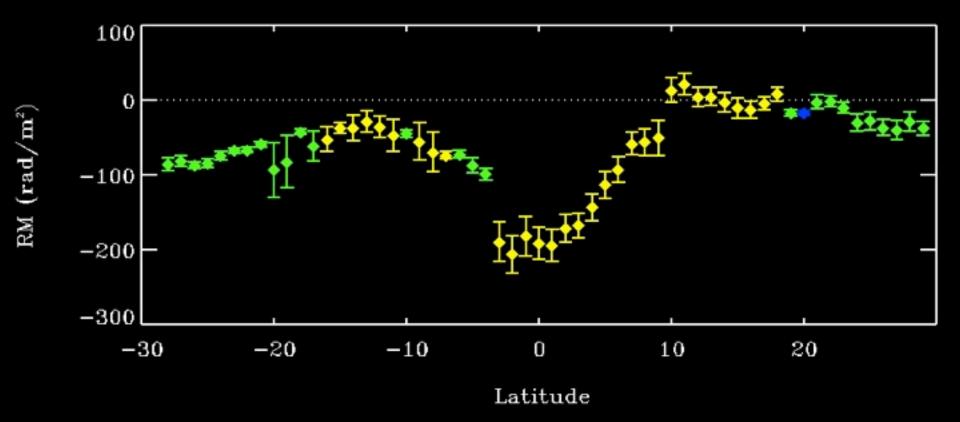ASS+Ring fits best to the recent VLA data.
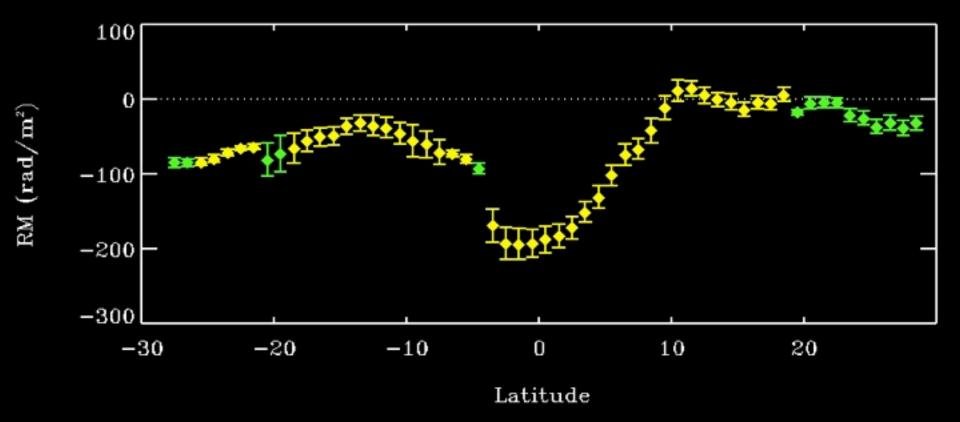(Van Eck et al. 2011)

Top 3 Contributions of the VLA Observations

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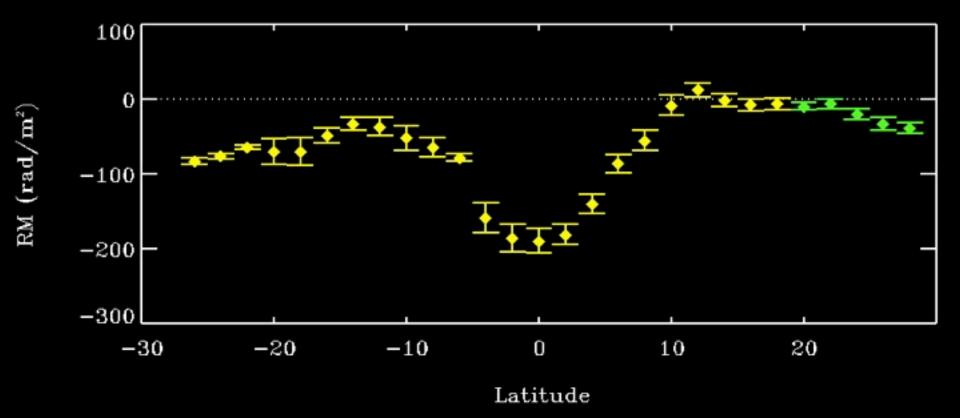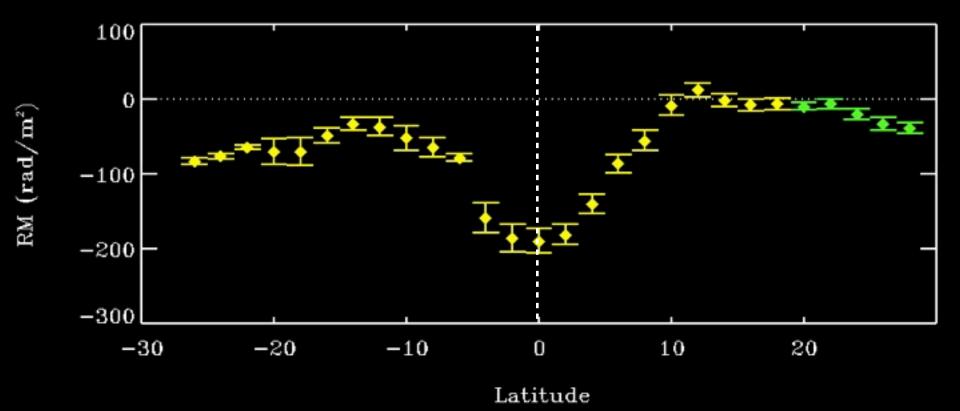
3. New model of the GMF

Figure 6 - Mao et al. 2012

Using CGPS-2012 + Mao et al. data

2 degree bins; 1 degree steps

Using CGPS-2012 + Mao et al. data

3 degree bins; 1 degree steps

Using CGPS-2012 + Mao et al. data

4 degree bins; 2 degree steps
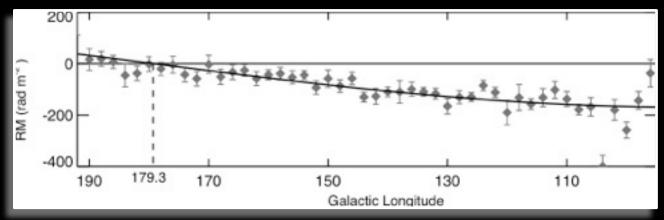
Using CGPS-2012 + Mao et al. data
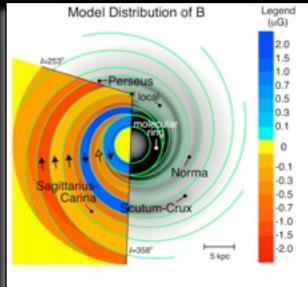

4 degree bins; 2 degree steps

=> *Symmetry around b=0; no warp signature*
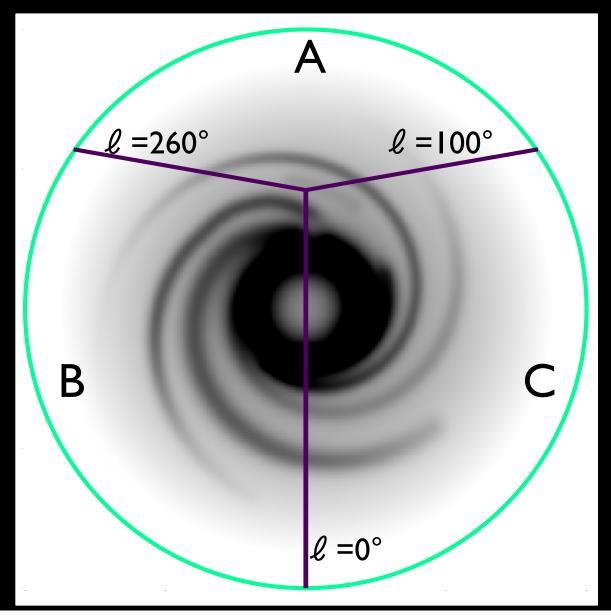
Top 3 Contributions of the VLA Observations

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What if the disk field is
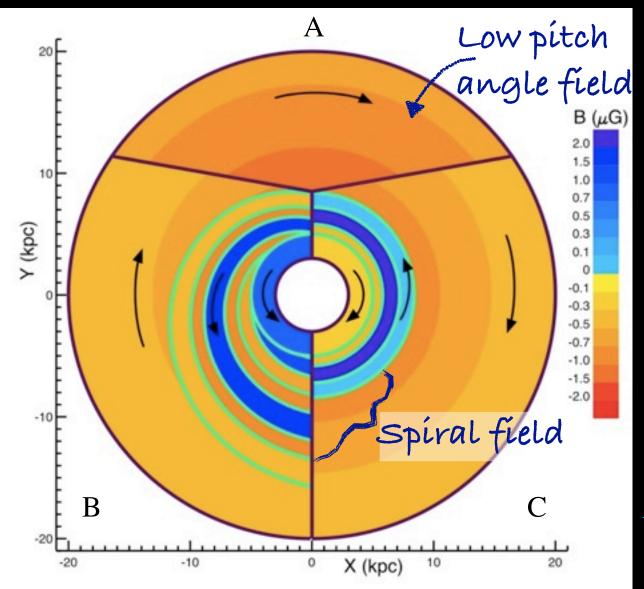BOTH
azimuthal and spiral?
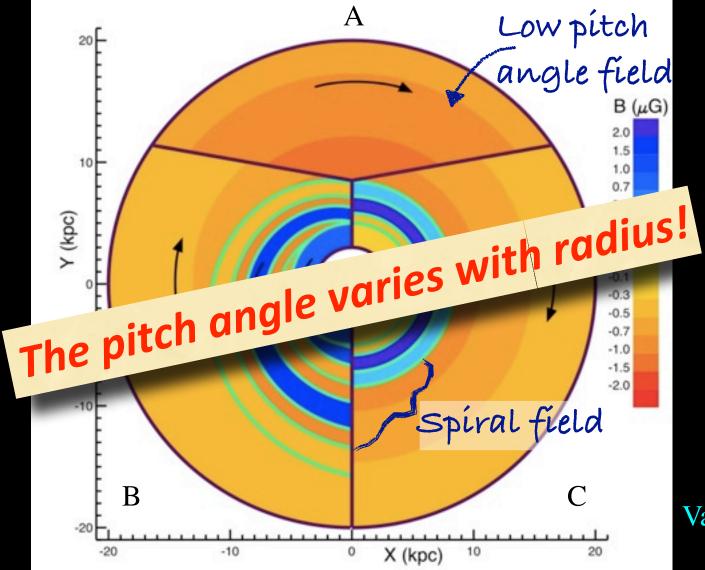
Piecewise Galactic Field Model

- Divided the Galaxy into three regions

- Modeled each region separately, without boundary conditions between regions

- Used RMs from CGPS (1020), SGPS (142), and VLA (194), plus pulsar RMs (557)
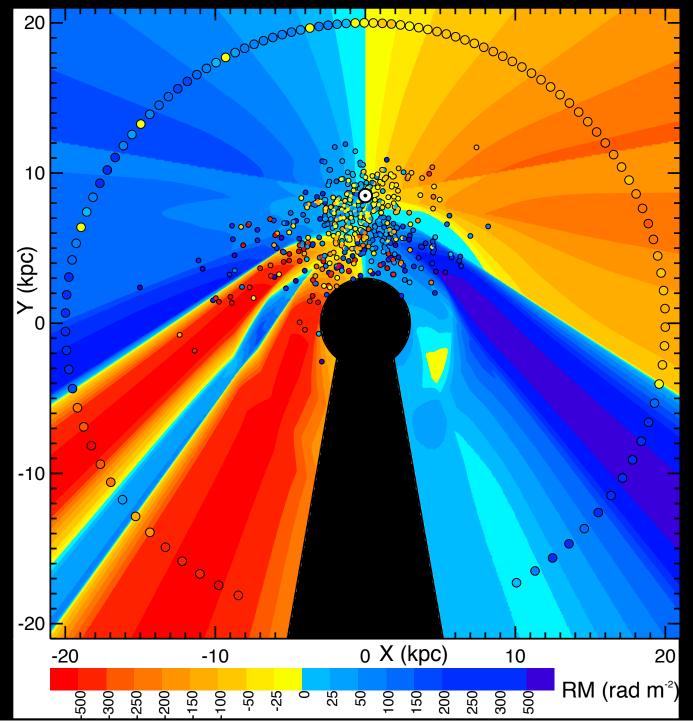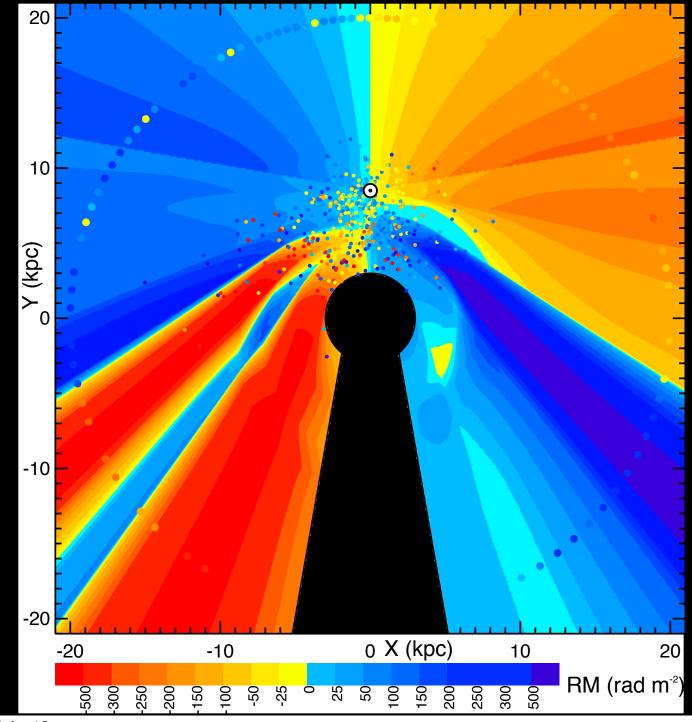
What we found….
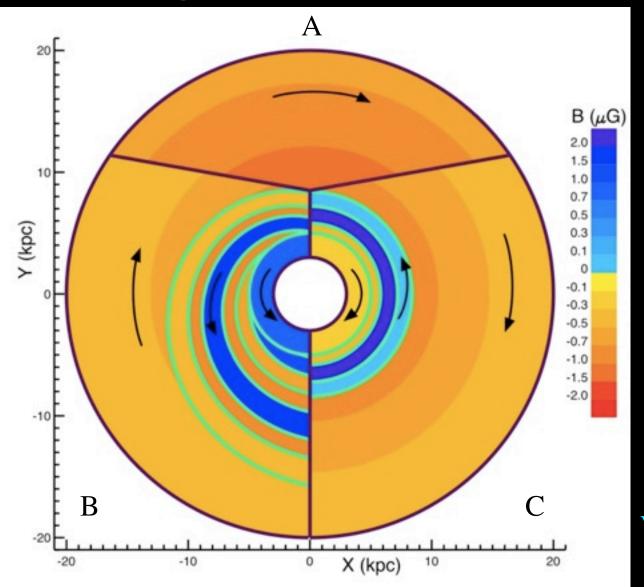

Low pitch angle field

Spiral field

Van Eck et al. (2011)

What we found....

Van Eck et al. (2011)

Magnetic Field Model

Van Eck et al. (2011)

Magnetic Field Model

Magnetic Field Model
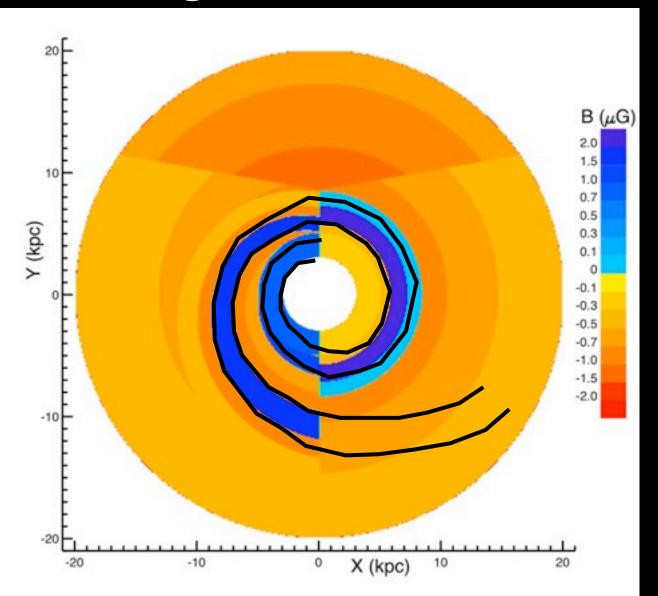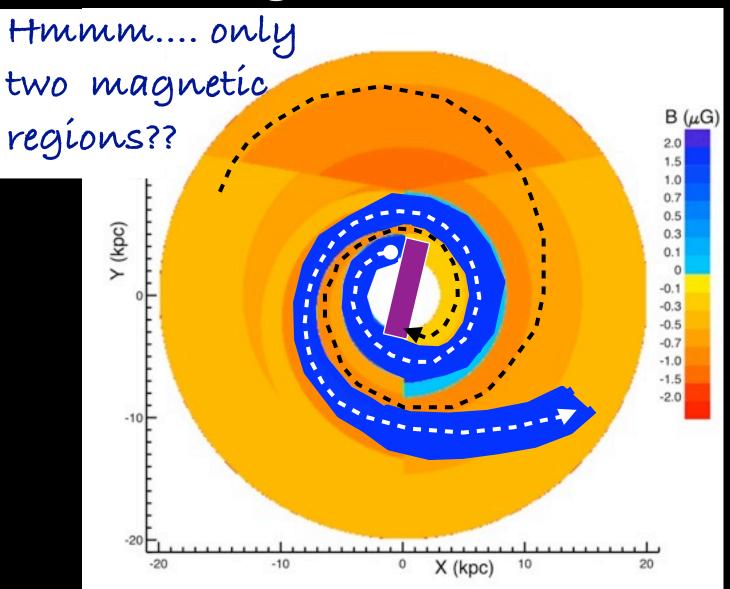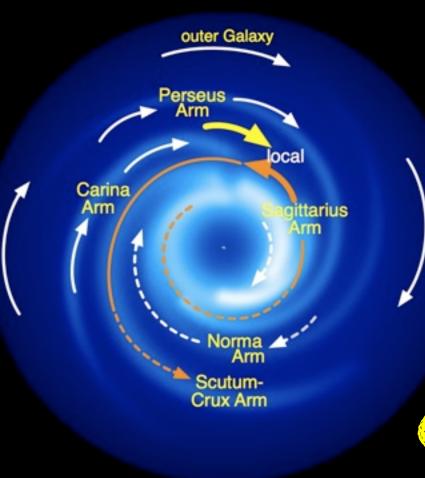
Magnetic Field Model

Hmmm.... only two magnetic regions??

Synthesized View of GMF

- Outer Galaxy: small pitch angle
- Inner Galaxy: larger pitch angle (aligned with arms?)
- <u>One reversed region</u> (spirals out from center?)
- Local, outer field is CW
- Sagittarius (Q1) and Scutum-crux (Q4) is CCW
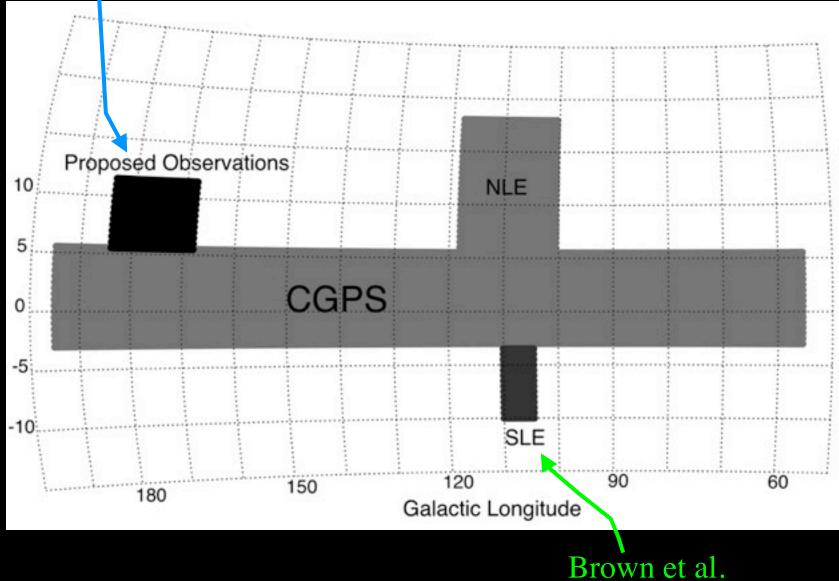
- MANY reversals not necessary.

Outline

- 'Recent' observations (CGPS, SGPS, VLA)

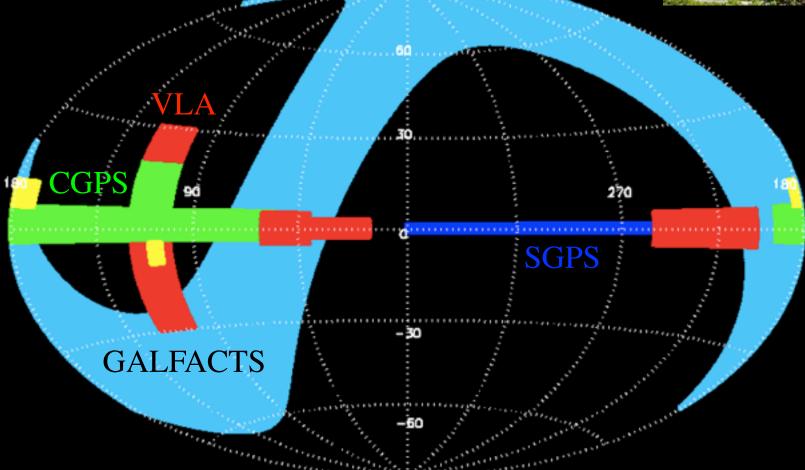- Interpretations of the data

- **Future directions**

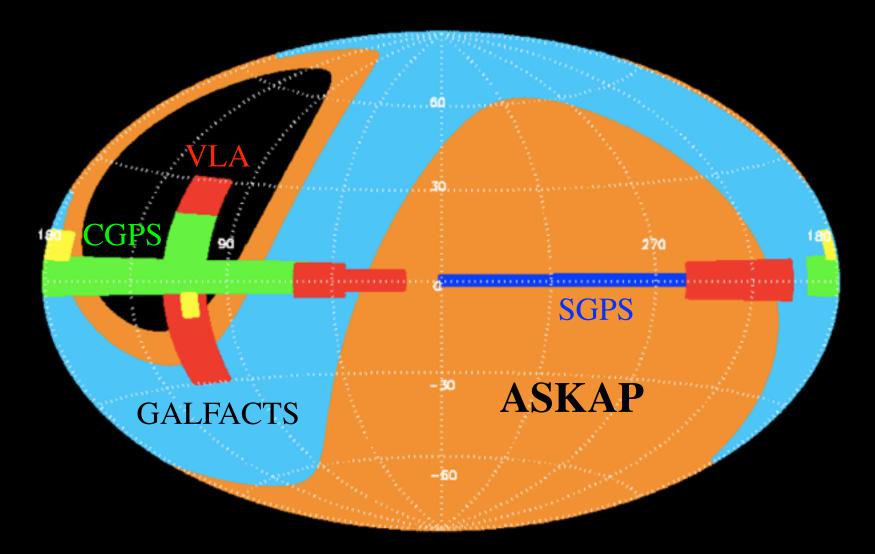# DRAO-ST Observations

GALFACTS

VLA

CGPS

GALFACTS

SGPS

ASKAP / POSSUM

Summary

- Goal of observations:
  - *To identify the appropriate constraints to determine how the field formed and is evolving (dynamo?)*
- Key Questions "Answered":
  - *Number of Reversals (1 reversed region)*
  - *Pitch angle varies with radius*
  - *(There is no warp signature - at least, not at l=109°)*
- Remaining motivating questions:
  - *Magnetic field scale height (RM ~ 1.1 kpc)*
  - *Cross-scale correlation*
  - *Disk-Halo Transition and Reconnection*

The End