Magnetic fields in our Galaxy and Beyond

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Grateful to cooperators

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K. Ferrier
Magnetic fields in Cosmic hierarchy

B-field: physically possible.

We made a long-term efforts to measure the B-fields of our Galaxy

B-fields have been well-measured in last tens of years

B-field has been measured for several centuries.

Evidence but no direct measurements

B-field has been measured for several centuries.

B-fields have been well-measured in last tens of years.

Earth

Solar system

Milky Way

Cluster of Galaxies

Cosmological structure
Magnetic fields in our Galaxy and Beyond

- **Background**
  - Optical sky, Radio sky and RM sky
  - Why B-field of our Galaxy
  - Definition and some problems

- **Magnetic fields of our Galaxy**
  - Galactic disk
    - Methods for detection of magnetic fields
    - Results
  - Galactic center
  - Galactic halo

- **Magnetic fields beyond our Galaxy**

- **Summary**
  - Which part by which probe
Gamma Sky

Radio Sky
Polarized Radio Sky

Faraday sky = RM sky

Anti-symmetry!
Astonished?
The Galactic contribution is dominating, in all aspects!

To know extragalactic or cosmological contribution (CMB):
The Galactic foreground contribution must be exactly known!
Yes? Somehow. But unfortunately not exact!
Why to study the B-field of our Galaxy

- Galaxy: a necessary key step from Sun to Universe!
- Important hints for B-origin: primordial or dynamo?
- Important roles in star formation
- Hydrostatic balance & stability in ISM:
  \[ \frac{B^2}{8} \pi = \rho \frac{v^2}{2} \]
  \[ B \sim 10^6 \text{G}, \rho = 10^{24} \text{gcm}^{-3}, \ v = 10 \text{km s}^{-1} \]
  (eg. Boilers & Cox 1990 for details)
- Key info for cosmic rays – propagation!
- Foreground for CMB?!

To understand the Galactic B-field, we have to measure first!

Knowledge on the Galactic B-field is far from complete!
Some notices

• Mention **different tracers** as possible!

• **Large-scale vs. small-scale:** 1 kpc

• **Review on large-scale magnetic structure**
  (exception: small-scale measurements related to the large-scale structure!)
  – Clouds measurements: No, but ...
  – Polarization on small ISM region: No!

• **Galactic structure:** not clear on arms, bar

• **Galactic ≠ galactic?**  **No!**  Careful !!

• **Modeled ≠ measured?**  **No!**
(Un)Known Structure of our Galaxy

How many arms?
Where are arms located?
Is there a bar in GC?
Galactic B-field: a decade ago

- Halo field: no idea!
- Disk field: A few kpc!
- Center: Poloidal field
- 30kpc
- 3 models: which?
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Observational B-tracers: What info out?

- **Polarization of starlight**: perpendicular field in 2 or 3 kpc
  
  orientation // $B_{⊥}$ —— 9000 +? stars

- **Polarization at infrared, mm, submm**: perpendicular field
  
  orientation // $B_{⊥}$ —— clouds or regions

- **Zeeman splitting**: parallel field, in situ (masers, clouds)
  
  $\Delta \nu \propto B_{∥}$ —— 137 maser regions & 17 coulds

- **Synchrotron radiation**: vertical field structures (added)
  
  total intensity $S \propto B_{⊥}^{2/7}$, $p\% \propto B_{⊥u}^2 / B_{⊥t}^2$

- **Faraday rotation**: parallel field, integrated (the halo & disk)
  
  $RM \propto \int n_e B_{∥} ds$ —— 1021 pulsars + >2000 EGSes
Starlight polarization:  \textit{local field // arm}

- 9000 stars have polarization measured
- mostly nearby (1~2kpc)
- polarization percentage increases with distance

Zweibel & Heiles 1997, Nature 385,131
Berdyugin & Teerikorpi 2001, A&A 368,635
Connection of Galactic B-fields of large and small scales

Beck et al. 1991, IAUS 146, 209

Distribution of molecular clouds and magnetic field lines in spiral arms with high (a), medium (b) and low star formation (c).

a) Many massive clouds \rightarrow\text{ tangled field structure}

b) Moderate number of medium size clouds \rightarrow\text{ tangled field in some places}

c) Too few clouds to hold all field lines in the disk
Polarization at mm, sub-mm, infrared

Working toward measure B-field of galactic scale

- Thermal emission (of dusts)
- Preferentially aligned by B

Hildebrand et al. PASP 112, 1215
Correlation of orientation of the fields in clouds with the large-scale Galactic B-field

(Results of SPARO 2003)

- Mapped large-scale magnetic fields in four GMCs
- Statistically significant correlation with the orientation of the Galactic plane.
- Field direction tends to be preserved during the process of GMC formation.
# B-field from maser spots


- Collect Zeeman splitting data of maser spots in HII and star formation regions
- Spots in one region always have the same field orientation!

<table>
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<th>Source (GL+GB)</th>
<th>Alias name</th>
<th>Dist (kpc)</th>
<th>Freq (MHz)</th>
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<th>$B_m$ (mG)</th>
<th>$B_u$ (mG)</th>
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</tbody>
</table>
The Galactic distribution of Zeeman data

Structure in distribution of field directions

*In situ* AU-B correlated in kpc scale!

Field reversals in radial!

We need more data, and better determined distances!

Han & Zhang 2007

*A&A* 464, 609
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  orientation $\parallel B_\perp$ ——— 9000 +? stars

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  $\Delta \nu \propto B_{\parallel}$ ——— 137 maser regions & 17 coulds

- **Synchrotron radiation**: vertical field structures (added)
  total intensity $S \propto B_\perp^{2/7}$, $p\% \propto B_{\perp u}^2 / B_{\perp t}^2$

- **Faraday rotation**: parallel field, integrated (the halo & disk)
  $RM \propto \int n_e B_{\parallel} ds$ ——— 1017 pulsars + >2000 EGSes
Synchrotron radiation: \textit{transverse $B$-structures}

Global $B$-field structure from linearly polarized emission

Two Possible origin of polarization:

\begin{itemize}
  \item \textit{Large-scale magnetic field as vectors shown (convention)}
  \item \textit{Anisotropic random field compressed by large-scale density wave}
\end{itemize}

RM maps helps on directions of (disk & halo field!)

MPIFR has a group working on this for \textbf{30 years}!

No information of $B$-\textit{directions}!

Han et al. 1999, A&A 384, 405
Radio Polarization surveys of Galactic plane
- show B-field structure:

• **Effelsberg Polarization Survey ©20cm**
• **Parkes 2.7GHz polarization survey**
• **Canadian Galactic plane survey**
• **Southern Galactic plane survey**
• **VLA Galactic plane survey**
• **Galactic Arecibo-LFA survey**
• **Urumqi polarization survey of our Galaxy at 6cm**
Sino-German Galactic plane polarization survey at 6cm

$10 < l < 230$

$-5 < b < +5$
Sino-German Galactic plane polarization survey at 6cm

Total Power GL: 143° – 183°

Polarized intensity GL: 143° – 183°
Fig. 8. Multiband images for the SNR G156.2+5.7. **Upper left:** superimposed X-ray image (blue), the recently published high resolution Hα image (green) and the $A_v$ extinction (red) of SNR G156.2+5.7. The image is taken from Fig. 9 of Gerardy & Fesen (2007) but rotated by ∼50° clockwise to align with the Galactic coordinate system. **Upper right:** the superposition of a ROSAT X-ray image (Voges et al. 1999) and contours showing $\lesssim$6 cm total intensities and vectors showing the magnetic field direction. **Lower left:** the superposition of a low resolution Hα image (Finkbeiner 2003) and with $\lesssim$6 cm data as before. **Lower right:** the superposition of 100 μm IRAS image (Wheelock et al. 1991) and the $\lesssim$6 cm data as before.
Both surveys have absolute zero-level.

PI at 22.8 GHz

WMAP-3yr

(Page et al. 2007)

Depolarization

PI at 1.4 GHz

DRAO+Villa Elisa

3D-model: Sun et al., 2008
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**Pulsars as best probes for Galactic B-field**

- **Polarized + no intrinsic RM:** Faraday rotation: $\text{RM}>0$, field toward us

$$ RM = \frac{e^3}{2\pi m_e^2 c^4} \int_{\text{Sun}}^{\text{PSR}} \left[ \frac{\lambda(l)}{\lambda_{\text{obs}}} \right]^2 n_e(l) B(l) \cdot dl = 0.820 \left\langle B_\parallel \right\rangle \int_0^{\text{Dist}} n_e dl $$

- $n_e$: can be measured:

$$ DM = \int_0^{\text{Dist}} n_e dl $$

$\implies$ the delay tells DM

$$ \Delta t = 8.3 \times 10^3 \frac{DM \Delta \nu}{v_3} \text{ sec} $$

$\implies$ the rotation of position angles tells RM value

**Average field strength can be directly derived**

$$ \left\langle B_\parallel \right\rangle = 1.232 \frac{RM}{DM} \mu G $$

**FARADAY EFFECT**
RM of Extragalactic radio sources

\[ RM = \frac{e^3}{2\pi m_e c^4} \int_{\text{source}}^{\text{Sun}} \left[ \frac{\lambda(l)}{\lambda_{\text{obs}}} \right]^2 n_e(l) B(l) \cdot dl \]

\[ \text{RM}_{\text{obs}} = \text{RM}_{\text{intrinsic}} + \text{RM}_{\text{InterGalactic}} + \text{RM}_{\text{MilkyWay}} \]

- **RM\text{intrinsic}**: RM intrinsic to the source;
  - They never know each other: uncorrelated \(\rightarrow\) Random!
  - Location of emission regions: \(\rightarrow\) Beam size?

- **RM\text{InterGalactic}**: RM from intergalactic space;
  - weak correlated if with same intervening medium
  - Small values ??

- **RM\text{MilkyWay}**: Foreground RM from our Galaxy;
  - Correlated \(\sim 10^9\) with same intervening ISM
  - Strongly depends on the Galactic coordinates!
Pulsars: Best probes for Galactic magnetic field

Widely spread in the Galaxy!

Parkes PSR survey

⇒ 3-D B-field structure!
## Major observations of pulsar RMss

<table>
<thead>
<tr>
<th>Authors</th>
<th>No. of RMs</th>
<th>No. New RMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamilton &amp; Lyne (1987)</td>
<td>163</td>
<td>119</td>
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<tr>
<td>Rand &amp; Lyne (2004):</td>
<td>27</td>
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<td>Qiao et al. (1995)</td>
<td>48</td>
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<td>Han et al. (1999)</td>
<td>63</td>
<td>54</td>
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<td>Weisberg et al. (2003)</td>
<td>36</td>
<td>17</td>
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<tr>
<td>Han et al. (2006):</td>
<td>223</td>
<td>196</td>
</tr>
<tr>
<td>Noutsos et al. (2008)</td>
<td>150</td>
<td>43</td>
</tr>
<tr>
<td>Han et al. (2009 to submit!)</td>
<td>477</td>
<td>400</td>
</tr>
</tbody>
</table>

*First big step!*  
*2nd big step!*
Pulsar RM\(\text{s}\) observed by others

\(|b| < 8 \text{ degree}\)
63+223 RM by Parkes (Han et al. 1999, 2006)

$|b| < 8$ degree
63+223+477 RMGs by Parkes +GBT
(Han et al. 1999, 2006, 2009)

$|b| < 8$ degree
Pulsar RMIs observed by others

$|b| > 8$ degree
63 + 223 RM by Parkes (Han et al. 1999, 2006)

\[ |b| > 8 \text{ degree} \]
63+223+477 RMs by Parkes +GBT (Han et al. 1999, 2006, 2009)

|b| > 8 degree
Modeling or Measuring

- When few data available, you like to model it to guess the unknown!

  Three models for limited number of data

- When data are enough to delineate what you want, just do measuring!

? Which model is the best
Paired probes to measure $B$-field in a region

$$RM \propto \int ne \, B_{//} \, ds$$
$$DM \propto \int ne \, ds$$

$$\left< B \right>_{d_1-d_2} = 1.232 \frac{\Delta RM}{\Delta DM} \mu G$$

Analysis is not limited to modeling $B$ all the path, but can measure $B$ in the region between! Significant improvement!

No worry about foreground bubbles! Less sensitive on Dist!
Measuring the B-field in the Norma arm

red: new measurements by Parkes 64m telescope

Measuring $B$-field in tangential regions!

$$\left\langle B_{\parallel} \right\rangle = 1.232 \frac{\Delta RM}{\Delta DM} \mu G$$

Random $B$ causing the scattering of data, gives uncertainties of $\langle B \rangle$. 
**Measured** magnetic field in the Galactic disk by pulsar rotation measures *(Han et al. 2006)*

- *always counterclockwise in arm region!*
- *clockwise in interarm region?*
- *More data still needed!*

![Graph showing measured magnetic field patterns in the Galactic disk.](image-url)
RM$ \propto \int ne B_{//} ds$

$\text{Model!}$

$\text{Pulsars}$

$\text{EGS}$

RM$ \propto \int ne B_{//} ds$

$\text{Model!}$

$\text{Pulsars}$

$\text{EGS}$
**RM**s of Extragalactic radio sources

\[ \text{RM} = \frac{e^3}{2\pi m_e^2 c^4} \int_{\text{Sun}}^{\text{source}} \left[ \frac{\lambda(l)}{\lambda_{\text{obs}}} \right]^2 n_e(l) B(l) \cdot dl \]

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**Common term!**
RM sources from extragalactic RM sources near Galactic plane: Consistent with B-Structure from pulsar data!

- PSR and EGRs data show a consistent B-structure!
- Dominant RM contribution from tangential regions!
RM data of pulsars and radio sources

By Jinhua Han
Oct. 1st 2005
RM data of pulsars and radio sources

By Anlin Han
Oct. 1st 2008
RM data of pulsars and radio sources

Preliminary
RM distribution of pulsars and EGRs

By Jinlin Han
Oct. 1st 2008

- RM = -27
- RM = -300
- RM = -2700
  (B away from us)

- RM = 27
- RM = 300
- RM = 2700
  (B towards us)
More B info from pulsar data?
Measured Radial dependence of regular field strength

\[ B_{\text{regular}}(R) = B_0 \cdot \exp\left[ -\frac{(R - R_\oplus)}{R_B}\right] \]

\[ B_0 = 2.1 \pm 0.3 \, \mu G \]

\[ R_B = 8.5 \pm 4.7 \, \text{kpc} \]

Uncertainties reflect random fields!

\[ \langle B_\parallel \rangle = 1.232 \frac{\Delta RM}{\Delta DM} \, \mu G \]

Galactocentric Radius R (kpc)
More B info from pulsar data?
Many Simulations of dynamos

--- check spatial B-energy spectrum & its evolution

e.g. Magnetic energy distribution on different spatial scales ($k = 1/\lambda$)

Many papers by
• N.E. L. Haugen, A. Brandenburg, W. Dobler, ..... 
• A. Schekochihin, S.C. Cowley, S. Taylor, J. Moron, ..... 
• E. Blackman, J. Maron ..... 
• Others ..... 

No measurements of the B-energy spectrum!
Measuring the B-field fluctuation vs scales

\[ RM = \int_{Sun}^{PSR} n_e(l)B_\parallel(l)dl \]
Spatial magnetic energy spectrum of our Galaxy


By pulsar RM/DM

Flatter B-energy spectrum at scales larger than the ISM energy-injection-scale!

λ < ~4 pc: 3D Kolmogorov
80 > λ > ~4 pc: 2D turbulence?

Email from A. Minter

Minter & Spangler 1996
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**Galactic center: filaments and polarization**

- **Poloidal fields:**
  - Nonthermal filaments: more discovery!
  - cm-polarization obs: RMs and intrinsic field

- **Toroidal fields**
  - submm, mm polarization: clouds
  - RMs of background radio sources

- **Field structure and field strength**
  - mG in filaments?
  - Zeeman splitting: mG field
  - uG in pervading regions?
Nonthermal radio-emitting filaments features
Large scale magnetic fields and relativistic electrons
SNRs, HII regions
Poloidal magnetic field within ~100 pc of nucleus

Wide-Field Radio Image of the Galactic Center
\( \lambda = 90 \text{ cm} \)
(Kassim, LaRosa, Lazio, & Hyman 1999)

Galactic Plane
New Galactic Center Survey
(high-resolution polarimetric)
(Lang et al.)
Magnetic fields in Galactic center
- traced by dust polarization (sub-mm and mm)
- oriented along the plane and perpendicular to NTFs
- a possibility: poloidal field sheared into toroidal field?

Chuss et al. (2003)
Nishiyama et al. (2008)
Poloidal & Toroidal fields near GC

**Toroidal fields**
(Novak et al. 2003, 2000)
- permeated in the central molecular zone (400pc*50pc)
- sub-mm obs of p%
- toroidal field directions determined by averaged RMs of plumes or SNR!

**Poloidal field**
filaments Unique to GC --- dipolar geometry!
(Morris 1994; Lang et al. 1999)
Magnetic fields in our Galaxy: near GC

(from B.D.C. Chandran 2000)
RMs of background radio sources for B-field in the GC region (Roy et al. 2008)
**Galactic center: filaments and polarization**

- **Poloidal fields:**
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  - cm-polarization obs: RMs and intrinsic field

- **Toroidal fields**
  - submm, mm polarization
  - RMs of background radio sources

- **Field structure and field strength**
  - mG in filaments: Yusef-Zadeh & Morris (1987)
  - Zeeman splitting of HI or OH lines: mG field
  - uG in pervading regions:
    Nord et al. (2004); Roy et al. (2008): 20uG
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The largest edge-on Galaxy in the sky

Pulsars and extragalactic radio sources as probes

Faraday Rotation Sky: Anti-symmetry!
Outliers significantly different from surroundings been filtered

RM<0 :<B> away from us

RM>0 :<B> to us

\[
RM = \frac{e^3}{2\pi m_e^2 c^4} \int_{\text{source}} \frac{\lambda(l)}{\lambda_{\text{obs}}} \frac{1}{n_e(l)} \mathbf{B}(l) \cdot dl
\]

The largest edge-on Galaxy in the sky

Pulsars and extragalactic radio sources as probes
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
Only about 1400 RMs available in literature up to now...

We have used Effelsberg -100m telescope to make a RM survey of 1800 sources, enlarge the cover density by a factor of three in most sky area......
Faraday Rotation Sky
Currently available data

Brown et al. 2003
Brown et al. 2007
**Local vertical B components: from poloidal field?**

**North Galactic Pole**
more RM<0

**South Galactic Pole**
more RM>0

_Bz_= 0.2~0.3μG pointing from SGP to NGP

*(Effect of the NPS discounted already!)*

*(see Han & Qiao 1994; Han et al. 1999)*
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