Wide Field Polarimetry

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1. Science with wide field stellar polarization measurements
2. RoboPol: proof of concept
3. WALOP: a proposed instrument for 3D tomography of Galactic dust and magnetic fields
Dust and interstellar polarization

- Dust grains are aligned with their short axes along the magnetic field.
- In emission, the E field is aligned with the long axis: polarization perpendicular to field.
- In absorption, radiation with E field along the long axis is preferentially absorbed: polarization parallel to field.
- Most stellar polarization arises from this dichroic extinction.

![Diagram of dust grains aligned with magnetic field, with E vector arrows indicating polarization directions.]
Tracers of the Galactic magnetic field

- Polarized synchrotron radiation from the ISM
- Extragalactic rotation measures (RM)
- Dust emission
- Radio pulsars (RM)
- Stellar optical polarization

\[
\text{RM} = 0.81 \int n_e B \cdot dl \quad \text{rad m}^{-2},
\]

\[B\] has units of \(\mu\text{G}\), \(n_e\) has \(\text{cm}^{-3}\), and \(dl\) has \(\text{pc}\).

All these feed into \textbf{models} of the Galaxy:
distributions of ionized medium, dust, cosmic rays, and magnetic fields
Planck synchrotron polarization

Planck arXiv:1506.06660

Planck+WMAP combined polarization at 20-50 GHz

Polarized intensity, with polarization angle encoded in color
C-BASS 5 GHz polarization

Polarized intensity, Stokes $(Q^2 + U^2)^{1/2}$, on a linear intensity scale.

Polarized intensity, with color indicating EVPA (magnetic field direction)

*Preliminary unpublished data*
Planck dust map

Planck Collaboration X 2015
arXiv:1502.01588

Intensity at ~ 353 GHz

Polarized intensity, Stokes ($Q^2 + U^2)^{1/2}$

CMB foreground!
Masking B-modes
(e.g. BICEP2)
Planck dust polarization

Planck Collaboration X 2015
arXiv:1502.01588
Extragalactic rotation measures

Pulsar rotation measures

Han, J L et al 2014 PoS AASKA14

3D information

Figure 3: The RM distribution of 736 pulsars located within $|b| < 8^\circ$ projected onto the Galactic plane. The background shows the approximate locations of spiral arms used in the NE2001 electron density model (Cordes & Lazio 2002). RMs of extragalactic radio sources (Xu & Han 2014b) located within $|b| < 8^\circ$ are displayed in the outer ring according to their $l$ and $b$, with the same convention of RM symbols and limits. The derived large-scale structure of magnetic fields in the Galactic disk are indicated by arrows. See Han (2013) for details.
Fig. 3. Map of interstellar polarization at high northern galactic latitudes: rectangular projection. The map shows the latitude range from 30° to 70°. The length of the bar is proportional to the value of polarization \( P \). Thin vertical dashed lines show the eastern (255° < \( l \) < 300°), central (300° < \( l \) < 360°), and western (0° < \( l \) < 45°) latitude zones of the magnetic loop. Thick dashed lines show the outer walls of Wolleben’s S1 and S2 shells and the thick solid line shows the contour of the interaction ring between the Local Bubble and Loop I (see Sects. 8.2 and 8.3 for explanation).

Stellar polarization


DiPol-2 polarimeter on 60 cm KVA telescope at La Palma
(single star per exposure, rotatable polarization modulator)
Goals:

• Develop an efficient, wide-field polarimeter for stellar polarization
• Designed to measure polarization with high significance for >20 stars/deg$^2$
• Control systematic errors to 0.2% in polarization, to detect stars in low-dust regions of sky
• Use with Gaia parallaxes to construct a 3-dimensional map of the Galactic magnetic field:
  • **Gaia will measure $\sim 10^9$ stars, with $\sim 10^6$ brighter than 16 mag**
Science with WALOP

- Physical models of interstellar dust, its emission and absorption, polarization properties, and grain alignment
- Mapping the Galactic magnetic field
- Understanding and modeling dust emission polarization at microwave frequencies, to help subtract foreground emission from CMB B-mode measurements (extrapolation in frequency)
- Other astrophysics:
  - star-forming clouds and role of fields in star-formation
  - MHD instabilities, turbulence, and amplification of field
  - dynamic recycling of material along field lines (“Galactic fountain”)
  - back-tracing sources of UHE cosmic rays deflected by magnetic fields
RoboPol Instrument

*in operation at Skinakas 1.3m telescope, Crete*

No moving parts, single exposure:

- the pupil is split into two halves, each incident on a half-wave retarder followed by a Wollaston prism (WP)
- the blue WP splits the rays in the horizontal plane for $Q$
- the red WP splits the rays in the vertical plane for $U$
- every point in the sky is projected to 4 points on the CCD
- 4 images measure $I \pm Q, I \pm U$
- $q = Q/I, \ u = U/I$
RoboPol image

Figure 1. A field observed by RoboPol. Each star in the field creates a quadruplet of images (spots) on the CCD. The central dark region is the mask used for lowering sky noise for the target at the centre of the field of view and the cross-like figure is created by the mask-supporting legs.
RoboPol blazar time series

Red: rotation events

Blinov et al 2015 MNRAS 453, 1683
Are rotation events associated with flares?

Green: RoboPol season
Beige: rotation events
Red: detected flares
Blue curve: flare model
RoboPol field stars (Polaris Flare)

Panopoulou et al 2015
MNRAS 452, 712

641 stars, median $p = 1.3\%$

ordered field pattern aligned with dust filaments (intrinsically polarized stars omitted)

Figure 16. Polarization segments over plotted on top of the 250-µm dust emission image of the Polaris Flare from the online archive of the *Herschel* Gould Belt Survey. The length of each segment is proportional to the debiased fractional linear polarization ($p_d$) of the star. The horizontal segment at the bottom-right corner is for scale. The blue star marks the position of the North Celestial Pole.
RoboPol field stars

Polarization percentage versus R magnitude

Shows we can reliably detect polarization ~ 0.2% even in region of low dust (Planck 353 GHz)
WALOP concept

• No moving parts
• I, Q, U in single exposure
• Separation of images onto 4 CCDs
• Careful control of systematic errors
• Instrumental calibration by scanning standard stars across field
## WALOP specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of view</td>
<td>30 arcmin sq</td>
</tr>
<tr>
<td>Detector array</td>
<td>4096 x 4096, 15 μm pixels</td>
</tr>
<tr>
<td>Assumed telescope diameter</td>
<td>1.3 m</td>
</tr>
<tr>
<td>Exposure</td>
<td>10 min</td>
</tr>
<tr>
<td>Magnitude R</td>
<td>16.4</td>
</tr>
<tr>
<td>Polarimetric sensitivity</td>
<td>$\sigma(p) \sim 0.2%$</td>
</tr>
<tr>
<td>Number of exposures for full sky</td>
<td>16,502</td>
</tr>
</tbody>
</table>
Conclusions

• Wide-field surveys of stellar polarization have great potential for Galactic structure studies

• Such surveys are feasible with the technology demonstrated by RoboPol

• We are developing collaborations to build a prototype WALOP and demonstrate it on telescopes in Greece, India, South Africa, or Chile

• A deep full-sky survey is conceivable

Thanks to Ramaprakash, Kostas Tassis, Vaso Pavlidou, and the RoboPol collaboration
The RoboPol Collaboration

Goals:

- Observe a large, well-defined sample of blazars in linear polarization with high cadence.
- Apply rigorous statistical methods to identify rotation events and study correlations with optical, radio, and γ-ray flares.

- **Caltech, California**: O. King, M. Baloković, T. Hovatta, T. Pearson, A. Readhead, A. Mahabal
- **University of Crete, Greece**: V. Pavlidou, D. Blinov, N. Kylafis, G. Panopoulou, I. Papadakis, I. Papamastorakis, P. Reig, K. Tassis
- **MPIfR, Bonn, Germany**: E. Angelakis, I. Myserlis, L. Fuhrmann, S. Kiehlmann, J. A. Zensus
- **IUCAA, India**: A. Ramaprakash, P. Khodade, C. Rajarshi, R. Rouneq
- **Nicolaus Copernicus University, Toruń, Poland**: A. Kus, R. Feiler, B. Pazderska, E. Pazderski
RoboPol

- Skinakas, Crete, Greece (University of Crete)
- elevation 1750m
- 1.23m Cassegrain
- seeing 0.7 arcsec
- automated operation
- adaptive observing strategy

Dedicated to this project ~4 days per week May–Dec for 3 years