Magnetic Field Strengths and Grain Alignment Variations in the Local Bubble Wall

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Outline of Talk

• Intro to polarization, grain alignment theory and the Local Bubble
• Archival data used for study and assumptions made
• Variations in the Local Bubble Wall
  • Geometric effects
  • Grain alignment
  • Magnetic field strength
ISM Polarization

- ISM polarization caused by asymmetric dust grains aligned with magnetic field
  - Unpolarized light is randomly orientated
  - Passing through magnetic field polarizes light (aligns in common direction)

- Allows us to:
  - Understand grain alignment
    - Understand dust characteristics and radiation field
  - Trace magnetic fields
  - Measure magnetic field strength (Chandrasekhar-Fermi Method)

Grain Alignment Theory

• Radiative Alignment Torque (RAT) theory
  • Grains “spun up” by torques imparted by a radiation field
  • Grain then precesses around magnetic field
  • Grain begins to “wobble” – torques turn spin axis to line up with magnetic field

• Other factors to consider
  • Size, shape and minerology
  • Density and turbulence (disalignment due to gas-grain collision)
Local Bubble

- Low density, ionized cavity in ISM surrounded by higher density material
- Wall of bubble traced by Sodium Absorption line measurements
- Estimated angle of wall ($\Psi$) using these maps (Lallement et al. 2003)

Archival Data Used

• 3D maps of Local Bubble (Lallement et al. 2003)
  • Used equivalent widths of the interstellar NaI D-line at 5890 Å and NaI absorption measurements (Welsh et al. 1994, Sfeir et al. 1999) to create maps by mapping iso-equivalent width contours

• Polarization %, direction (Berdyugin et al. 2014)
  • Polarization maps of the regions around the north ($b>30^\circ$) pole from data obtained with the DiPol polarimeter installed on 60 cm telescope and from past observations (Berdyugin & Teerikorpi 2002, Berdyugin et al. 2004) for a sample size of 2400 stars with distances of up to ~800 pc

• UBV photometry (Høg et al. 2000)
• JHK photometry (2MASS)
• Trigonometric parallax (Gaia DR2, DR1 & Hipparcos)
• Spectral Type (Wright et al. 2003)
• Combined, we have 1,066 stars with reliable $A_V$
Assumptions Made

• Assumed fixed parameters:
  • Size, shape and minerology of the grain distribution
  • Gas density (implications of variations discussed later)
• Magnetic field follows the Local Bubble wall
  • Can use wall angle to account for large-scale projection effects
• Disalignment constant (given fixed gas density)
• Can show that turbulence is (relatively) constant
Constant Turbulence

- Extracted line width b-values from multiple surveys to cover full sky
- Line width of gas if roughly constant
  - Exceptions in third quadrant
    - Larger variations in Crawford (1991) data, small compared to polarization data (discussed later)
    - Largest variation in Welty et al. (1996) data, most likely not tracing LBW gas kinematics though

- K I: Welty & Hobbs (2001), spec. reso. ~0.4-1.8 km/s, yellow
- Ca II: Welty et al. (1996), spec. reso. ~0.3-1.2 km/s, green
- Na II & Ca II: Crawford (1991), spec. reso. ~3.6 km/s, black and red
Geometric Effects

- As mentioned, need to account for large-scale projection effects due to LBW angle with line of sight
- Allows us to separate (inherent) polarization efficiently and (observed) fractions polarization
- Not applicable to regions where mean direction in magnetic field is close to line of sight
- Preformed Student’s t-test
  - 93.9% likelihood we are able to distinguish between these two types of regions
  - $\bar{\beta} = 0.15 \pm 0.04$ for $\Psi < 13^\circ$
Grain Alignment Variations

• With characteristics of dust grains and gas assumed (or shown fixed), consider grain alignment variations

• Variations in distance
  • Could be due to additional “screens” besides LBW, would introduce errors in subsequent analysis

• Variations in longitude
  • With previous assumptions, this due to some primary aligning mechanism
Grain Alignment Variations - Distance

• Fit $A_V$ and $p$ distributions with one and two component Gaussians

• Identify regions where two component Gaussian favored and means separated by $> 3\sigma$

• Distance to second screen is distance to nearest star
Grain Alignment Variations - Distance

• Identified six regions with some step increase
• All steps consistent with Local Bubble wall distance
• Observe these steps as an inhomogeneous screen can have properties similar to screen
• As seem to only observe effects of “clumpy medium”, will assume single extinction and polarization screen for all bins
• Noticed large spike in polarization around galactic center
• Want to quantify level of alignment for all regions to trace variation
Grain Alignment Variations - Longitude

- Evaluate grain alignment efficiency with fractional polarization ($p/A_V$)
  - Need to account for line of sight turbulence
- Jones et al. (1992) shows that in relationship:
  - $\alpha$ depends on turbulence of material
  - $\beta$ is sensitive to number alignable grains (fixed), grain alignment efficiency (want to evaluate), and orientation of the field (can account for via LB geometry)
- $\beta (\sin \Psi)^{-1}$ probe for grain alignment efficiency

$$\log \left( \frac{p}{A_V} \right) = \alpha \log(A_V) + \beta$$
Alignment Driving Mechanisms

• Nearby radiation field (per RAT theory)
  • Simply scale modeled radiation field at the LB wall distance to compared to alignment efficiency:
    \[ \beta (\sin \Psi)^{-1} (l, b) = A + B \sum_{i=1}^{n} \frac{L_i}{r_i^2} \]

• Variations could also be due to Galactic magnetic field
  • Modeled by: \( \beta (\sin \Psi)^{-1} (l, b) = a + c \sin (l - 80^\circ) \) (Crutcher et al. 2003)
Nearby Sources of Radiation

• Most likely to be nearby OB associations
  • de Zeeuw et al. (1999) conducted comprehensive census of OB associations within 1 kpc
  • Treat each OB association as point source with luminosity equal to sum of association candidates

• Also consider all spectrally classified nearby field stars
  • Michigan and Wright catalogs
Grain Alignment Variations - Longitude

- Radiation field at LBW distance highly correlated with observations
- Field due to blue sources best aligns with observations (expected in RAT theory)
Chandrasekhar-Fermi Method

• With polarization angle data, we are able to estimate the magnetic field strength in LBW

• Chandrasekhar-Fermi Method: \( \langle B_\perp \rangle^2 = \frac{4\pi \rho \Delta v_{los}^2}{\Delta \theta^2} \)
  
  • We have assumed the gas density to be constant
  • Shown turbulence to be constant for all lines of sight
  • Variations in magnetic field strength then inversely proportional to position angle dispersions
Chandrasekhar-Fermi Method

• Fit Gaussian to distribution of polarization angles for each region to find dispersion
• Similar to grain alignment, observe variation in polarization angle dispersions
  • Low dispersion in similar regions as larger grain alignment efficiency
Polarization Angle Dispersion Variations

- Andersson & Potter (2006) found that $\Delta \theta = 26 \pm 4^\circ$ towards the Southern Coalsack ($l, b = 300^\circ$)
  - Our observations consistent with this in regions of lower grain alignment efficiency
- Spearman’s Rank Order Correlation test: 0.03% probability dispersion random with respect to $\beta$
Polarization Angle Dispersion Variations

• As mentioned, turbulence roughly constant, but still small variations
  • Not comparable to dispersion though

• Assumed density to be constant
  • For magnetic field strength to be constant in LBW, there would have to be a large (~factor of 25) decrease in density towards Galactic center

• Alternative is correlation between low PA dispersion and grain alignment efficiency, feel this is probably the case

\[
\langle B_\perp \rangle_i^2 = \langle B_\perp \rangle_o^2 \frac{\rho_i \Delta v_{\text{los},i} \Delta \theta_i^2}{\rho_o \Delta v_{\text{los},o}^2 \Delta \theta_o^2}
\]
Polarization Angle Dispersion Variations

• With this correlation, this would indicate OB associations are drivers of bifurcation in some way

• As stated, LB shaped internally by supernovae and stellar winds
  • OB associations could provide similar flows compressing wall in these regions

• With magnetic field parallel to wall and frozen in plasma, compression would cause increased strength
  • Density in regions would also stay same, or increase, not decrease
Results Summary

• Modeling the grain alignment as due to a dominant alignment mechanism accurately reproduces the data
  • This supports radiatively driven grain alignment
  • Demonstrates that polarimetry could potentially be used to probe radiation fields

• Correlation in grain alignment efficiency and relatively higher magnetic field strength suggests compression of LBW

• Addition of multi-band polarimetry and accurate space density measurements would allow further tests of the theory