Tracing Interstellar Magnetic Field Using Velocity Gradient Technique: Application to Atomic Hydrogen Data

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Abstract

The advancement of our understanding of MHD turbulence opens ways to develop new techniques to probe magnetic fields. In MHD turbulence, the velocity gradients are expected to be perpendicular to magnetic fields and this fact was used by González-Casanova & Lazarian to introduce a new technique to trace magnetic fields using velocity centroid gradients (VCGs). The latter can be obtained from spectroscopic observations. We apply the technique to GALFA-Hi survey data and then compare the directions of magnetic fields obtained with our technique to the direction of magnetic fields obtained using PLANCK polarization. We find an excellent correspondence between the two ways of magnetic field tracing, which is obvious via the visual comparison and through the measuring of the statistics of magnetic field fluctuations obtained with the polarization data and our technique. This suggests that the VCGs have a potential for measuring of the foreground magnetic field fluctuations, and thus provide a new way of separating foreground and CMB polarization signals.

Key words: ISM: general – ISM: magnetic field – ISM: structure – magnetohydrodynamics (MHD) – radio lines: ISM

1. Introduction

Turbulence is ubiquitous in astrophysics. The Big Power Law in the Sky (Armstrong et al. 1995; Chepurnov & Lazarian 2010) shows clear evidence that interstellar turbulence extends over 10 orders of magnitude of scales in the interstellar media (ISM). The ISM is magnetized and therefore the turbulence is magnetohydrodynamic (MHD) in nature (e.g., Li et al. 2014; Zhang et al. 2014; Pillai et al. 2015).

The modern theory of turbulence has been developed on the basis of the prophetic work by Goldreich (1995, hereafter GS95). The original ideas were modified and augmented in subsequent theoretical and numerical studies (Lazarian & Vishniac 1999; Cho & Vishniac 2000; Maron & Goldreich 2000; Cho et al. 2001; Lithwick & Goldreich 2001; Cho & Lazarian 2002, 2003; Kowal & Lazarian 2010; see Brandenburg & Lazarian 2013 for a a review).3 The Alfvénic incompressible motions dominate the cascade. This cascade can be visualized as a cascade of elongated eddies rotating perpendicular to the local direction of the field.4 Naturally, this induces the strongest gradients of perpendicular to the magnetic field. Thus, one can expect that measuring the gradient in turbulent media can reveal the local direction of magnetic field. This property of velocity gradients was employed in González-Casanova & Lazarian (2017, hereafter GL17) to introduce a radically new way of tracing magnetic fields using spectroscopic data.

3 We do not consider the modifications of the GS95 model that were intended to explain the spectrum $k^{-7/2}$, which was reported in some numerical studies (e.g., Boldyrev 2006). We believe the reason for the deviations from the GS95 predictions is the numerical bottleneck effect, which is more extended in the MHD compared to hydro turbulence (Beresnyak & Lazarian 2010). This explanation is supported by high resolution numerical simulations, which corresponds to GS95 predictions (see Beresnyak & Andrey 2014). The simulations also strongly support the anisotropy predicted in GS95 and rule out the anisotropy prediction in the aforementioned alternative model.

4 The notion of the local direction was not a part of the original GS95 model. It was introduced and justified in more recent publications (see Lazarian & Vishniac 1999; Cho & Vishniac 2000; Maron & Goldreich 2000).

5 We refer the reader to Draine et al. 2011 for a detailed discussion of the various methods. Draine et al. 2011 applied velocity centroid gradients (VCGs) to synthetic maps obtained via MHD simulations and obtained a good agreement between the projected magnetic fields and the directions traced by the VCGs. As the velocity centroids can be readily available from spectroscopic observations (see Esquivel & Lazarian 2005), this provides a way not only for observational tracing of magnetic fields, but also for finding its strength using the GL17 technique, which is similar to the well-known Chandrasekhar–Fermi method.

Motivated by the GL17 study, in this paper we calculate the VCGs using H i data from the GALFA survey (Peek et al. 2011) and compare the directions of the magnetic fields that we trace using the gradients to the directions of magnetic fields, which are available from the PLANCK polarization survey (Adam et al. 2016).5 To do this, we first significantly improve the procedure of calculating the VCGs and test it with numerical data. Our recipe for calculating the VCGs is presented in Section 2. In Section 3, we apply the technique to trace magnetic fields. We discuss our results in Section 4, and our conclusions are presented in Section 5.

2. Improved Procedure for Calculating Velocity Gradients

GL17 established that the VCGs can trace a magnetic field in MHD turbulence. However, this exploratory study lacks a criterion for judging how well gradients can trace magnetic fields. Therefore, it is difficult to judge what the resolution requirement to trace magnetic field vectors is and what the uncertainties are. Therefore, our first goal is to introduce a robust but quantitative procedure that can produce reliable gradient map depending only on the physical conditions of the region we are examining, but not the resolution of the map.

5 Based on observations obtained with Planck (http://www.esa.int/Planck), an ESA science mission with instruments and contributions directly funded by ESA Member States, NASA, and Canada.
We used a single fluid, operator-split, and staggered grid MHD Eulerian code ZEUS-MP/HK, which is a variant of the well-tested code ZEUS-MP (Norman 2000; Hayes et al. 2000), to set up a three-dimensional, uniform, isothermal, supersonic, and sub-Alfvénic turbulent medium. We adopted periodic boundary conditions. The initial cube was set with a uniform density and an initial uniform field. Turbulence was injected solenoidally continuously (e.g., Ostriker et al. 2000; also see the Appendix of Otto et al. 2017). Our simulations had the resolution of 792\(^3\). We selected two cubes with a sonic Mach number \(M_s = 5\) and an Alfvénic Mach number \(M_A = 0.6\) but with a different initial magnetic field orientation (one was parallel to the \(z\)-axis, another is at the angle \(\pi/7\) to the \(z\)-axis). Compared to the GL17, we used higher resolution simulations and studied the effect of varying magnetic-field direction relative to the line of sight.

To trace magnetic field, we generated polarization maps by projecting our data cubes along the \(x\)-axis, assuming that the dust producing the polarization followed the gas, and was perfectly aligned by the magnetic field. Let \(\phi = \tan^{-1}(B_y/B_x)\), where \(B_{yz}\) are the \(y\) and \(z\) directions of magnetic field. The intensity \(I\), velocity centroid \(C\), and Stokes parameters \(Q\), \(U\) were computed by

\[
\begin{align*}
I(r) &= \int \rho(r, x)dx \\
C(r) &= I^{-1} \int \rho(r, x)v_x(r, x)dx \\
Q(r) &\propto \int \rho(r, x)\cos 2\phi dx \\
U(r) &\propto \int \rho(r, x)\sin 2\phi dx,
\end{align*}
\]

where \(r\) is the vector on the \(y-z\) plane. The polarization angle is given by \(\phi_{2d} = 0.5\tan^{-1}(U/Q)\). Polarization traces the magnetic field projected along the line of sight.

We calculated velocity centroids following GL17 but modified the VCGs calculations to increase the accuracy of the procedure. In particular, we performed cubic spline interpolation, which uses a three-point estimate to provide the maps for gradient study. The resulting map is 10 times larger than the original one. To search for maximum gradient direction in each data point, we selected a neighborhood of the radius vector \(r \in (0.9, 1.1)\) pixels in the interpolated map. The interpolation process is accurate with a 3\(^\circ\) error, and is comparable to the Sober operator used in Soler et al. (2013). We smoothed our data with a \(\sigma = 2\) pixels Gaussian kernel.

The statistical properties of gradient fields can determine the mean direction of magnetic fields in a subregion of interest. We divided our synthetic maps into subregions and examined the statistical behavior of gradient vector orientation (the absolute angle (AA)) and relative angle (RA) \(\phi\) between gradients and fields within the region. The top four panels of Figure 1 show what distributions of the AA and RA look like when the size of the block decreases. As the block size increases, the mean gradient direction becomes more well-defined. The alignment between the gradient and magnetic field also becomes more clear as block size increases. We find that when the block size arrives at \(100 \times 100\), a sharp distribution emerged with well-defined mean and dispersion. By measuring the mean of the AA distributions, we determined the mean magnetic field direction within the respective block. The RA distributions told us how accurate this prediction of magnetic fields is. We called this treatment subblock averaging in the following sections. On one hand, notice that subblock averaging is not a smoothing method. It is used to increase the emphasis of important statistics and suppress noise in a region and to provide an estimate on how accurate this averaging is by the AA-RA diagram. On the other hand, smoothing does not provide such an estimate. A detailed discussion of how white noise affects the subblock averaging and smoothing is provided in an extended paper by Lazarian et al. (2017), where a companion new measure, namely synchrotron intensity gradients, is studied.

The benefits of our approach can be seen in Figure 2. We divided the whole simulation domain into 16 blocks with equal size and predicted the magnetic field direction in each block. As one can see from these figures, the VCGs trace well-magnetic fields. We also confirmed this for synthetic observations when the line of sight was at different angles compared to the mean direction of magnetic field.

Chandrasekhar & Fermi (1953, C-F) provide an expression relating the strength of plane-of-sky magnetic field by dispersion of turbulent velocities \(\nu\) and polarization vectors \(\theta\) in magnetized turbulence. For an improved C-F method, see Falceta-Goncalves et al. (2008):

\[
\delta B \sim \sqrt{4\pi \rho \frac{\delta \nu}{\delta \phi}}.
\]

The mean magnetic field strength can also be calculated using the same concept in subblock averaging. The dispersion of VCGs and magnetic-field directions are not exactly the same, but the difference is small. GL17 introduced a factor \(\gamma\) of \(\sim 1.29\) to account for this difference. In our case, using our improved procedure of gradient calculation, we got the dispersion of the VCGs in blocks just 1.07 times that of polarization. The standard deviation of the ratio of the dispersions is 0.05. As illustrated in GL17, the factor \(\gamma\) varies with parameters of MHD turbulence. Elsewhere we shall provide a fitting expression for \(\gamma\) as the function of \(M_s\) and \(M_A\). This should further increase the accuracy of obtaining the value of magnetic field strength. More details on the technique of obtaining magnetic field intensity using only spectroscopic information and not polarimetry information will be provided in our forthcoming paper (K. H. Yuen & A. Lazarian 2017, in preparation).

3. Application to Observation Data

With the tested procedure in hand, we selected diffuse regions from observation surveys. We acquired data from the Galactic Arecibo L-Band Feed Array H I Survey (GALFA-H I). We compared the VCGs directions to the PLANCK polarization data. In diffuse media, polarization of emitted radiation is perpendicular to local magnetic field direction (Lazarian 2007; Andersson et al. 2015), i.e., the same way as the VCGs. To adapt the difference of resolutions, we adjusted the block size used in Planck to reflect the same physical block referred to in GALFA.

The region we selected from GALFA-H I survey data spans R.A. 15°–35° and decl. 4°–16°. The bin size along the velocity axis is 0.18 km s\(^{-1}\). We analyzed 353 GHz polarization data obtained by the Planck satellite’s High Frequency Instrument (HFI).\(^7\) We performed the same procedure as indicated in

\(^7\)We use the \textit{planckpy} module to extract polarization data in a particular region with J2000 equatorial coordinate: (https://bitbucket.org/ezbh/planckpy/src).
Figure 1. Top four: the distribution of absolute angle (red) and relative angle (blue) in a synthetic map of size $792 \times 792$ for subregions of size $33 \times 33$, $50 \times 50$, $99 \times 99$, and $198 \times 198$, respectively. The Gaussian profile emerges when the patch is $1/8$ of the total length of the map. The profile is well-defined when it is $1/4$ of the map. Bottom four: the distributions of absolute angle (red) and relative angle (blue) from observation data for subregion of size $50 \times 50$, $100 \times 100$, $200 \times 200$, and $300 \times 300$ (relative to GALFA-H I data resolution), respectively.
Top 16 panels: the distribution of AA (red) and RA (blue) in a synthetic map from run-2 with a block size of $198 \times 198$. By detecting the peak of the AA distribution, we determined the mean magnetic field direction within the block. Bottom panel: the predicted mean magnetic field vector (red) compared with the real magnetic field vector (blue). The background is the intensity of the synthetic map.

Figure 2.
Section 2. We checked the AA and RA, as shown in the bottom four panels of Figure 1, to pick an appropriate block size for a gradient vector. For the given case, a $100 \times 100$ block satisfies the requirement in the recipe. The velocity gradient vectors are plotted with the polarization vectors in Figure 3. In this region, most of the gradient vectors align very well with polarization vectors. The detailed study of the observed deviations from the perfect alignment will be provided in our subsequent publication.

Following GL17, we provide a comparison to the alignment magnetic field as traced by polarization and the intensity gradients. In our region of interest, the emission intensity of atomic hydrogen is proportional to its column density. The column density gradients were shown to act as tracers of magnetic fields (Soler et al. 2013). Figure 5 shows the histograms of relative orientations between velocity and intensity gradient vectors to polarization. In agreement with the theoretical expectations as well as the results in GL17, our
improved procedure of calculating the VCGs shows that the latter are much better aligned with polarization compared to the intensity gradients. Indeed, nearly 80% of the VCGs are within 45° deviation from the polarization direction compared to 61% of the intensity gradients.

4. Discussion

4.1. Structure Functions of Velocity Gradients

The structure functions of polarization and gradient fields also allow us to study how well-aligned they are. As the statistics of polarization are dependent on the Alfvénic Mach number \( M_A \) (Falceta-Goncalves et al. 2008), the close relationship between rotated the VCGs and magnetic fields suggests that gradient statistics should have a behavior similar to the polarization statistics. To compare the VCGs to polarization in synthetic maps, we extended the subblock averaging algorithm to every point of our map and computed the structure function in terms of the orientation \( \theta \) of gradient/polarization vectors:

\[
SF_2(r) = \left( \langle \theta(r') - \theta(r' + r) \rangle \right)^2.
\] (3)

The statistics of dust polarization are important for studying magnetic field turbulence (Falceta-Goncalves et al. 2008) and for cleaning the CMB polarization maps. If we want to do the same using VCGs, it is important test to what extent the statistics of the VCGs are similar to those revealed by polarization. The left and middle panels of Figure 4 show the power spectra \( P_s(k) \) and second order structure functions \( SF_2(r) \), respectively, of the VCGs orientation and the polarization angle. In terms of the spectra, both VCGs orientations and polarization gradients exhibit a \(-2\) slope. We also examined the structure functions for polarization and the VCG distributions from the observation data using the same procedure. The right panel of Figure 4 shows the structure function computed using observation data, where the \(+1\) slope also emerged.

4.2. Comparison with Other Techniques and Earlier Papers

This paper presents the first application of the VCGs to observational data arising from diffuse media. By comparing the results obtained with the VCGs and PLANCK polarization data, we demonstrated the practical utility of the VCG for tracing of magnetic fields and obtaining statistical information about magnetic field in this diffuse region.

The gradient techniques have a big advantage over other techniques for estimating magnetic field direction and strengths; these techniques only require an easily available centroid. Unlike the PLANCK map, the VCG maps do not require unique multi-billion dollar satellites, but instead can be routinely obtained with the existing spectroscopic surveys. By using different species, one can distinguish and separately study different regions along the line of sight. Combining the VCGs that traces magnetic fields in diffuse gas with polarimetry (e.g., ALMA polarimetry) that traces magnetic fields in molecular clouds, one can study what is happening to magnetic fields as star formation takes place. This may be a way to test different predictions (e.g., the prediction of magnetic flux removal through the reconnection diffusion process; Lazarian 2005, 2014; Lazarian et al. 2012).

The alignment of density gradients was previously explored by Soler et al. (2013). The alignment of these gradients with magnetic field is also due to the properties of turbulence. For instance, Beresnyak et al. (2005) showed that the GS95 turbulence can, in some situations, imprint its structure on density. However, density does not trace turbulence as directly as velocity does. Therefore, we expect more deviations of density gradients from the magnetic field direction compared to the velocity gradients. Our study confirms the conclusions in GL17, which says that the VCGs provide a better tracer. We expect that the density gradients are related to the filaments, which align with magnetic fields as reported in Clark et al. (2015). Therefore, we also expect that the VCGs trace magnetic fields better than the filaments.

However, we have to stress that this region is only a particular example on how VCGs work, which does not represent it is applicable everywhere without cautious on the limitations. One should understand that both density and velocity properties are important components of MHD turbulent cascades. Therefore, the deviations of the gradients from the magnetic field direction are informative. For instance, we observe an a different behavior of VCGs and density gradients in the regions of strong shocks as well as in self-gravitating regions (K. H. Yuen & A. Lazarian 2017, in preparation). Therefore, there is important synergy of the simultaneous use of VCGs, density/intensity gradients, and polarimetry. Adding to the list the newly suggested technique of synchrotron intensity gradients, which is discussed in a new paper by Lazarian et al. (2017), increases the wealth of the available tools. This opens new ways of exploring magnetic fields in the multi-phase ISM.

We would also like to point out that while the polarimetry directions in Figure 3 seem to be well-aligned over significant patches of the sky, this does not mean that there is no turbulence there. The correspondence of the VCGs and polarization directions can be understood only if the media is turbulent. The power-law behavior of the statistics related to both the VCGs and polarization directions confirms this. The fact that the power law does not correspond to the GS95 slope is due to the effects of the emitting region geometry as it discussed in Cho & Lazarian (2002, 2009).
5. Conclusions

Our work provides a promising example on how the VCG technique introduced in GL17 traces magnetic fields in ISM. In the paper:

1. we provide a new robust prescription for calculating the VCGs and test this new approach using the synthetic data obtained with MHD simulations.
2. we show that the estimates of magnetic field strength based on the C–F approach can be improved with the new prescription.
3. we apply the VCGs to the available high latitude H\textsc{i} GALFA data and demonstrate an excellent alignment of the direction of the VCGs and those measured by the PLANCK polarization.
4. we show that the statistics of the fluctuations measured by the VCGs and polarization have the same slope for both synthetic and observational data, which suggests that VCGs could potentially be promising tool for accounting for polarized foregrounds within CMB studies.
5. the differences between the directions defined by the polarization, the VCGs, and the intensity gradients carry information about the turbulent interstellar medium and this calls for the synergetic use of the three measures.

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