Cosmic & Fermi-bubble B-fields in γ-ray Helicity

1 Introduction

We propose to use the technique of "odd-correlators" to image the cosmological magnetic field helicity, as well as the Fermi-bubble helicity. This permits us to discriminate between both cosmological and Fermi-bubble models that have ordered versus chaotic magnetic fields. Ordered fields are characteristic of long-lived traps, whereas chaotic fields are characteristic of temporally evolving disturbances. Therefore γ-rays can potentially resolve disputes about the origin of cosmological and galactic magnetic structures.

1.1 Magnetic Helicity

Definition: The phrase "magnetic field" or "vector potential" peaked in popularity in 1964, according to Google Ngram analytics, while "helicity", "differential geometry", and "topological invariant" peaked in 1990, but "magnetic helicity" in 2001. What is this quantity that is so late to the hipster math party? Magnetic helicity is defined to be $\int \mathbf{A} \cdot \mathbf{B} dx$, where $\mathbf{A}$ is the magnetic vector potential and $\mathbf{B}$ is the magnetic field vector. Since $\mathbf{B}$ can also be written as $\nabla \times \mathbf{A}$, the integral can be seen as a measure of the "twisting" of vector potential, like the threads on a screw. The real advantage to this quantity, is that like angular momentum, the helicity is conserved much better than either magnetic field or vector potential separately.[1] Then measurement of galactic or cosmic helicity are excellent probes for the primeval conditions that gave rise to the magnetic fields in those regions.

Significance: Helicity also has the property of amplifying the magnetic field. The average solar magnetic field of 1 Gauss (up to 4kG in sunspots) is attributed to a self-generated (reversing every 11 years) dynamo in the convective outer zone of the sun, where a small amount of twist is lifted and amplified by a "self-dynamo" tapping into the energy gradients. Similar plasma motions are possible in accretion disks of neutron stars, in the stellar disks of the galaxy [2], and in the "Chern-Simons" term [3] of the early Big Bang, all of which can use helicity to amplify magnetic fields.

Helicity also interacts with the motion of charged particles. For example, every 11 years when the Sun has positive helicity, cosmic rays can diffuse into the heliosphere more readily than when it has negative helicity.[4, 5] If the Big Bang exhibited strong helicity while the neutrinos were still coupled to the field, then not only would it pump up the cosmic magnetic field strength, but the sign of the helicity would bias the neutron to proton ratios and change the nucleosynthesis models.

Finally, since the helical magnetic fields possess a coherence length comparable to the size of a galaxy or galaxy cluster, they can both efficiently store energy and release it in jets as in AGN or long-duration gamma-ray bursters. Cosmic rays, which can be a source of GeV gamma rays, are both accelerated and directed by magnetic fields. Whether the GeV energizing mechanism is a direct jet, or an indirect stochastic acceleration, magnetic fields play a role, and the origin of those magnetic fields is related to helicity. Therefore measuring the helicity of galactic or cosmic magnetic fields is an important step to recreating the time-evolution of the magnetic fields–their origin, growth and decay–which are a necessary part of any model of GeV gamma rays.

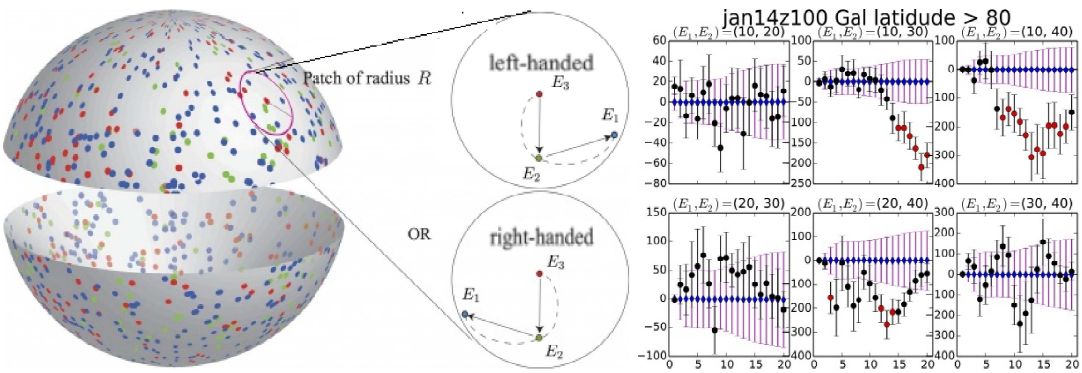

Figure 1: Left: Color-coded high energy γ-rays detections on the celestial sphere. Inset shows helicity of three successively lower energy γ-rays. Right: Total helicity grouped by energy into 10GeV bins, where x-axis is the radius (in degrees) of the red circle in left panel.

Measurement: Since noise is isotropic, and diffusion goes as the square of the gradient, they are both even functions of the distance vector. Magnetic helicity changes sign if the order is inverted, so it is an odd function of the distance and odd correlators of the data will highlight underlying helicity while averaging out the even functions. The simplest odd correlator is the volume of a parallepiped given by the triple vector product: $\mathbf{a} \cdot \mathbf{b} \times \mathbf{c}$. See left panel of Figure 1, where the direction vectors (E_1, E_2, E_3) correspond to (**a,b,c**).

Tashiro et al., Tashiro and Vachaspati[6, 7] argue that if **c** is the direction of a TeV blazar or high energy gamma-ray, and **a, b** are the directions of successively lower energy gamma-rays, then the triple product will "light-up" in a torus around the blazar jet, where lower energy cascade photons are produced by intermediate charged particles spiralling along the magnetic field. The radius of this torus depends on the energy of the charged particles, which may account for the different "peak" positions seen for differing energies in the right panel of Figure 1. The radius of this torus also depends upon the strength of the magnetic field, and Chen et al. [8] use Fermi-LAT to estimate this width and from that determine an intergalactic field strength after many approximations.

Despite this tour-de-force, as many new questions arise as were answered. All known point sources of GeV γ-rays were excised from the data set to concentrate on the diffuse background, yet the initial 50 GeV γ-rays were assumed to be from unseen point-source TeV blazars. Likewise, the northern galactic pole seems to have a considerably stronger helicity than the southern, for reasons not understood. Finally, the Milky Way magnetic helicity is assumed to be zero, despite the unavoidable helicity of a spinning galaxy with a finite magnetic field strength. As Chen et al. [8] remark in their last paragraph, "This raises the question if the Milky Way is somehow responsible for the signal we are detecting." In the next section we consider a possible way for the Milky Way to produce γ-ray helicity, which we argue may also explain Fermi-bubbles.[9]

1.2 Galactic quadrupoles

Definition: The magnetic dipole field of the Earth or the Sun is a well-known phenomenon used to explain the operation of magnetic compass, leading to N/S designation of magnetic poles. The quadrupole field is less well known, but is an inevitable consequence of having several dipole fields in proximity, where the two dipole fields vectorially cancel in two distinct locations, known as "cusps", located roughly above the poles, see left panel of Figure 2.

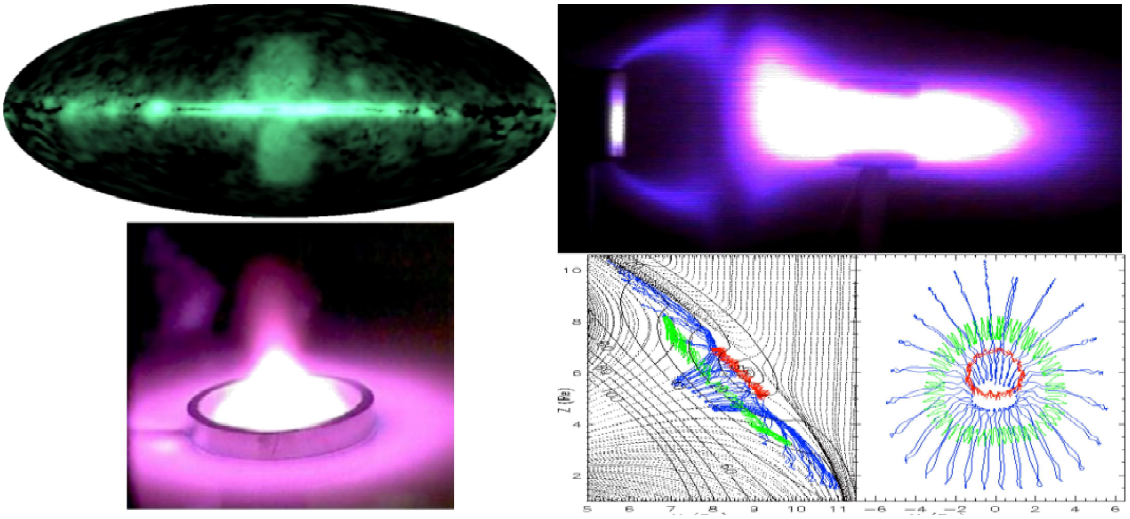

Figure 2: LfTp: Fermi-bubble imaged in IC γ-rays. RtTp: Double magnet quadrupole with cusp trapped plasma; LfBm: Annular quadrupole with central inflated cusp; RtBm: Electron orbits trapped in Earth's cusp.[13]

Galactic magnetic fields have been measured up to μG, (the Milky Way has inter-stellar magnetic field of $\sim 10\mu G$), so its interaction with the inter-galactic field will of necessity produce quadrupolar cusps.

Significance: Quadrupolar cusps are effective traps for energetic particles, and have been observed to efficiently heat these trapped particles by three or four orders of magnitude.[10, 11] In periods of low turbulence, which favor trapping, the pressure exerted by these trapped particles can dominate the magnetic topology, so that the cusps inflate and become lobe-shaped, as seen in the panels of figure 2. Trapped plasma can then be stochastically heated, which may not only explain the origin of the "Fermi-bubbles" observed over the poles of the Milky Way,[12] but may also explain the origin of galactic cosmic rays.[13]

Measurement: The fixed magnetic field direction and fixed charge produce a odd correlator in the particle motion that through inverse-Compton or synchrotron emission, transfers helicity to the gamma-ray spectrum. Examination of the particle tracing in right panel of Figure 2, show that both energy and pitch-angle affect the particle motion, so that gamma-ray energies are spatially correlated in the trap. Since the γ-ray emission from Fermi-bubbles are due to inverse-Compton and synchrotron radiation from quadrupolar trapped particles, then maps of the Fermi-bubbles should also light up the odd-correlators, as well as probe the strength of the magnetic field.

2 Fermi Data Analysis Procedure and Sensitivity

We repeat Chen et al. TeV blazar analysis using the Fermi Pass-8 data set with better statistics, to verify that the odd correlators are indeed still present and above the statistical noise. After excising 1-degree circles around known point sources of high-energy gamma-rays, the celestial sphere is divided into patches, where the highest energy diffuse gamma-ray in the patch is taken as vector$\mathbf{C}$. For lower energy gamma-rays out to a maximum radius R, the direction $\mathbf{B(R,E)}$ is determined. This can be done without binning to avoid discretization noise. With no loss of generality, $\mathbf{B} \times \mathbf{C}$ can be computed for this data set. Finally, under the requirement that $E(\mathbf{A}) < E(\mathbf{B})$, we can compute $Q = \mathbf{A} \cdot \mathbf{B} \times \mathbf{C}$ for triplet (A,B,C).

This dataset can be further binned into annular patches of R and $\Delta E = E(B) - E(A)$, where equal numbers of points are in each patch, and the average Q(R,E) recorded.

After uniform statistical binning, we also use uniform 5-degree latitude bins (suggested by Chen et al) and uniform longitude bins to test whether the Fermi-bubbles are visible in the odd correlator. We implement the inter-galactic helicity model of Tashiro and Vachaspati, as well as construct a model of the Fermi-bubble quadrupolar cusp trapping. We then use Monte-Carlo sampling to compare the observed odd correlator with the two models. Finally, we compare the chisquared significance of the two fits, to determine whether extra-galactic or Fermi-bubble magnetic fields are the best explanation of the excess in the odd-correlator. We also compute the odd correlator for chaotic magnetic fields in the Fermi bubble in order to compare our quadrupolar magnetic field model with other chaotic magnetic field models.

3 Science Objectives

Both galactic and extra-galactic helicity are of interest in cosmology. The first tells us about the formation of the Milky Way galaxy, and the second about the Big Bang Nucleosynthesis era. Because of the interaction between γ-rays and e-/e+ pair-production, γ-rays are a remote observation of magnetic field strength and helicity. If the big discovery in gamma-ray astronomy was that GRB's were extra-galactic, then it may be an equally important discovery that γ-rays can observe galactic cosmic rays. If so, then not only does this address the origin of the Fermi-bubbles, but it addresses the long sought origin of the galactic cosmic rays. So gamma-rays became a valuable probe of our own Milky Way galaxy, that despite its proximity, has hidden until now its global magnetic geometry from our prying eyes.

4 NASA Relevance and management plan

We expect our total level of effort for this proposal to be equivalent to about 0.5 FTE per year for 1 year. We have requested funding of 70 k$ for an year. Funded personnel will include a member of University of Alabama in Huntsville (UAH, N.Bhat), and Grassmere Dynamics (R. Sheldon). R. Sheldon (0.25 FTE) will lead the data analysis, N. Bhat (0.25 FTE) will help with the analysis code and interpretation of results, M. Briggs will assist the rest of us in interpretation of results and writing papers.

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