The Interstellar Magnetic Field in the Ionized Filament CXR 11

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Abstract. By studying the properties of polarised radiation in the Canadian Galactic Plane Survey images (Stokes Q and U in particular), we are developing techniques to deduce information about the interstellar magnetic field structure. Part of this investigation involves studying how the Faraday rotation properties correlate with radiation from components of the ISM, such as the ionized gas. We present preliminary results from a study currently being conducted on the ionized filament CXR 11, and discuss constraints on the magnetic field geometry within CXR 11.

1. Introduction

Interstellar magnetic fields are believed to be important in the formation and evolution of galaxies and stars, interstellar gas dynamics and the production of cosmic rays. Because they are very difficult to measure, little is known about their generation, evolution or morphology. We are attempting to infer topological and quantitative information about the magnetic field in the galaxy through observations and modelling.

The measurement of interstellar magnetic fields typically falls into two categories (Heiles, 1987); measurement of the strength of the parallel component ($B_{||}$ or line of sight component), and the measurement of the direction of the tangential component ($B_{\perp}$ in the plane of the sky). By examining the difference in polarisation angle of one line of sight at different wavelengths, Faraday rotation is often used as the basis for inferring $B_{||}$.

The Canadian Galactic Plane Survey (CGPS) is performing high resolution wide field polarimetry of diffuse polarised structures in the plane of the Milky Way. A special situation has been discovered in Cygnus X where a polarised feature passes behind the ionized source, Cygnus-X Ridge 11, CXR 11 (Wendker et. al., 1991). This polarised feature, referred to as “the eel”, is discussed in Peracaula et. al. (these proceedings). Figure 1 shows the Stokes I and U observations of CXR 11. The alternating dark and light regions in the center of Figure 1b represent rapid changes in polarisation angle producing a change in the sign of Stokes U. These striations constitute part of the eel. The distinct arch in the eel, coincident with the contours of CXR 11, is produced by the propagation of radiation from the eel through the magnetized plasma of CXR 11 resulting in a shift of the polarisation angle of the eel. This spatial change in
the polarisation angle allows for a single wavelength calculation of the parallel component of the magnetic field from simple Faraday rotation physics.

![CXR 11: Stokes I](image1.png) ![CXR 11: Stokes U with Stokes I contours](image2.png)

Figure 1. CXR 11 in a) Stokes I; b) Stokes U with Stokes I contours.

2. Calculations

As an EM wave propagates through a magnetized plasma, the direction of polarisation is “Faraday” rotated through an angle $\Psi$ [rad] given by

$$\Psi = \lambda^2 \times 0.812 \int n_e B \cdot dl = 0.812 \lambda^2 L < n_e B_\parallel >$$

(1)

where $\lambda$ [m] is the wavelength (21 cm), $n_e$ [cm$^{-3}$] is the electron density, $L$ [pc] is the pathlength and $B$ [$\mu$G] is the magnetic field. If it is reasonable to assume that $< n_e B_\parallel > \sim < n_e > < B_\parallel >$ then equation 1 yields an expression for $< B_\parallel >$:

$$< B_\parallel > \approx \frac{\Delta \Psi}{0.812 \lambda^2 < n_e > L}$$

(2)

Here, $\Delta \Psi$ is the change in rotation angle between two points off and on a region of enhanced $< n_e >$. This relationship can be rewritten in terms of the measured flux density $S$ [mJy/beam] using standard equations for emissivity, and assuming a filling factor of 1 and a cloud temperature of $10^4$K. Since we do not know the actual pathlength through CXR 11, we can parameterize this unknown in terms of the observed ridge diameter ($D$) by letting $L = \varepsilon D$ so that

$$< B_\parallel > \approx \frac{\Delta \Psi}{3.14 \times 10^5 \sqrt{S} \sqrt{\varepsilon} D}$$

(3)

By tracing the eel across CXR 11, we estimated $\Delta \Psi$ between the edge and center of CXR 11 as $90^\circ \pm 10^\circ$. With a flux density at the center of the ridge of $140 \pm 20$ mJy/beam and a width of approximately 1.5 pc, equation 3 yields a measure of $< B_\parallel > \sim 0.35/\sqrt{\varepsilon} \mu$G. This value for $< B_\parallel >$ is significantly smaller than the
typical ISM value of a few $\mu$G (Heiles, 1987) suggesting that the field alignment is close to the plane of the sky. The factor of $\sqrt{\varepsilon}$ also suggests that the ridge is probably a cylindrical filament, since a sheet would give rise to a factor of $\varepsilon >> 1$, thereby reducing $B_\parallel$ significantly.

3. Modelling

The analysis in the previous section allowed us to derive an average value for $B_\parallel$ through the filament. Here, we use a simple model to help infer qualitative features of the magnetic field geometry. The model (Figure 2) assumes a cylindrical filament of a width consistent with the observations, placed in front of a polarised background field with the same gradient structure as in the observations. With the model, we can produce a polarisation angle map that is consistent with a particular cylinder orientation, magnetic field, and electron density distribution. Currently, all implementations have a uniform electron density.

![Figure 2. Illustration of our model construction.](image)

For the first implementation of the model (Figure 3a) we consider a magnetic field aligned with the cylinder axis. The cylinder is tilted so that $B_\parallel$ is positive (directed away from the observer). Note that the direction and shape of the deflections in the polarisation angle of the background field are in agreement with observations. The second implementation invokes a helical field geometry with constant pitch angle. Figures 3b shows the result for a $B$ with a pitch angle of 0.6° with respect to the cylinder's axis. In this model, the cylinder is in the plane of the sky and the field strength has been adjusted so that $\Delta \Psi$ is 90° ± 10°. Our third implementation (Figure 3c) uses a field with the same helicity as in the previous case, but with the cylinder tilted in the same manner as in Figure 3a. The asymmetry in both 3b and 3c is induced by the reversal in direction of the parallel component of the azimuthal part of the field. In Figure 3b, the axial component does not contribute to $B_\parallel$, whereas in Figure 3c, the axial contribution cancels the azimuthal contribution in the right hand side of the cylinder. These effects become more pronounced when either the pitch angle or magnetic field strength is increased. The asymmetry of Figures 3b and 3c is not in agreement with the observations, suggesting that if the magnetic field in CXR 11 has a helical component, the pitch angle is very small.

4. Discussion

We have attempted to identify features of the magnetic field within the ionized hydrogen ridge CXR 11. Through Faraday rotation measurements, we estimate
the parallel component of the magnetic field to be positive and on the order of 0.35 $\mu$G. Through modelling we found that the magnetic field is likely dominated by an axially aligned field and, if it does contain a helical component, it is probably very small relative to the axial component.

This is a preliminary study. We have not attempted to identify the complete magnetic field structure since the modelling is non-unique, and the present observations only supply one component of the field. We are presently investigating the possibility of a polarisation study of the associated submillimeter radiation (from dust) in order to determine the direction of $B_\perp$ based on dust grain alignment with the magnetic field (Hildebrand, 1988). This would reduce the variables of the model, and bring us one step closer to describing the complete magnetic field.

The consistency of the magnetic field models used here with the implied current configurations has not been given proper consideration. Explicit accounting of the currents must be given when dealing with filamentary structures (Alfvén, 1981), and in fact may shed light on the formation details of CXR 11. The axial magnetic field model implies that the currents flow only in the azimuthal direction. We do not know at this point whether this is a reasonable configuration with respect to momentum balance considerations. Also, since a helical field is not likely given our observations, we may be able to rule out the possibility of filament formation via a “pinch effect”. In such a case, axial currents produce a toroidal magnetic field, which induce a force $i \times \mathbf{B}$ towards the axis, thereby causing compression of the plasma towards the axis. Since a toroidal field is a helical field with a pitch angle of 90°, this is difficult to reconcile with our observations.

References

Alfvén, H., 1981, *Cosmic Plasma*
Hildebrand, R.H., 1988, *QJRAS*, 29, 327
Peracaula, M., Taylor, A.R., Bellchamber, T.L., Gray, A.D., & Landecker, T.L. 1999, these proceedings