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The 'tomography' of the Galactic magnetic field

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Abstract

The morphology of the magnetic fields of the Milky Way is important information which forms the basis for our understanding of the Galactic radio emission. In the past 40 years considerable progress has been made mainly due to the various radio methods of remote sensing of magnetic fields. Driven by theoretical considerations and using pulsar Rotation Measure data in particular, a bi-symmetrical morphology model for the Galactic magnetic field was proposed. New observations of polarized radio continuum with high angular resolution, of extra-galactic radio sources in the Galactic plane and studies of individual pulsars near H II regions have shown that we have a much more complex situation. It is now clear that no one method can give a complete picture of the magnetic field morphology. In this contribution the old data will be discussed pointing out the limitations. New data will be presented that can give us as a possible way to a 'tomography' of the Galactic magnetic field.

1 Introduction

The magnetic field of the Milky Way can be investigated by various remote sensing methods, in particular in the radio spectral range. Optical polarization of starlight is caused by the alignment of dust grains in the magnetic fields of the Galaxy. This was the earliest method of observing the magnetic fields in our Galaxy. However the information thus gathered applied to the local spiral arm only. The radio Zeeman effect which is the ideal way to measure magnetic fields operates in dense molecular clouds, giving information about the local conditions, and thus it has only a limited application for the determination of the large-scale Galactic magnetic field. Radio continuum emission is a result of the synchrotron emission process in the magnetic fields in the emission regions. The linear polarization of this emission is a direct signature of magnetic fields. Radio waves propagating through a magnet-ionic medium suffer Faraday rotation. By observing at a number of frequencies we can probe different regions of the Milky Way. At high radio frequencies the information comes from the most distant regions of the Milky Way. The Faraday effect can be used to trace the magnetic fields in the line of sight. In particular extra-galactic radio sources (EGRS) and pulsars can be used to probe the Galactic magnetic fields. In view of the different regimes that each method probes, a combination of all the mentioned methods, a sort of 'tomography' must be performed to model the magnetic field of the Milky Way.

2 The 'old' data

The first evidence for magnetic fields in the Milky Way came from optical polarization observations interpreted in terms of the Davis -Greenstein effect. It soon became clear that these observations gave information about the local neighborhood, out to 1–2 kpc. A monumental collection of optical data are found in Mathewson & Ford (1970) or in Fosalba et al. (2002).

Clearly the general magnetic field of the Galaxy is oriented along the Galactic plane with some vertical directions associated with the local spurs of radio emission.

The next method that became available for remote sensing of magnetic fields was given by the detection of radio continuum that is due to the synchrotron emission process. Low frequency surveys trace the total magnetic field intensity. Equipartition arguments can give us an estimate of the magnetic field intensity. Numerous all sky surveys at low frequencies (below 1.4 GHz) have been published that show the signature of magnetic fields. Recently the WMAP satellite results gave us all sky maps at high radio frequencies (above 22 GHz). By observing the linear polarization we measure the $B_\perp$ in some (several) emission regions. Due to the passage of the linearly polarized emission through Galactic magneto-ionic medium, Faraday rotation is added and hence must be corrected for. Polarization mapping of the Galaxy was done in the 1960s and 1970s leading to the determination of rotation measure (RM) of the Galactic foreground by Spoelstra (1984). The values determined by Spoelstra were very low, around ± 10 rad m^{-2}, due to the low frequencies of observation, low angular resolution and undersampling of the sky.

The Zeeman effect is a basic method of measuring magnetic fields used both in optical and radio astronomy. However the Zeeman effect gives the values of magnetic fields in local H I or molecular clouds and is as yet of any help in entangling the large-scale Galactic magnetic fields. The Zeeman effect has a great potential if the sensitivity is increased by many orders of magnitude in the future observational facilities.

By observing the Faraday rotation of EGRS or pulsars, through the magneto-ionic medium of the Galaxy, we can determine the average $B_{||}$. Published catalogues of RM of EGRS (e.g. Simard-Normandin & Kronberg,1980) were widely used to model the 'Galactic magnetic field'. These data contain very few sources in the Galactic plane and hence were a probe of the nearby magnetic fields, away from the Galactic plane. Pulsar RM observations are performed predominantly in the plane of the Galaxy. In addition they give a measure of the magnetic field intensity since both the Rotation Measure (RM) and the Dispersion Measure (DM) can be determined. Pulsar data has been used to model the Galactic magnetic fields. However in the interpretation of these data the foreground RM was until now neglected because the results of Spoelstra (1984) suggested very low values. This is not so in view of recent observations and hence the foreground rotation effect must be corrected for. We must go back to every pulsar with RM determination and examine the field with Hα or radio H II data to ensure that these foregrounds have no effect on the observation.

The theoretically motivated interpretation of the magnetic field of the Milky Way as a bi-symmetrical spiral with many windings and several reversals (e.g. Sofue & Fujimoto 1983; Vallee 1984, 1996; Rand & Kulkarni 1989; Han & Qiao 1994; Han et al. 1999, 2002) was based first on EGRS data and later on pulsar RM observations. However no other nearby galaxy (e.g. Beck, this volume) shows such a structure. Also the pulsar data are not consistent showing many local reversals. There seems to be a main reversal in the magnetic field orientation between the local and Perseus spiral arms and the inner Sagittarius arm. Pulsar data are very scanty for the anticenter region where we have the advantage to observe through only one Faraday screen.

3 The new data

The new era of studies of Galactic magnetic fields starts with the high resolution observations of Wieringa et al. (1993). In these interferometric observations at 327 MHz small scale structures on the scale of ∼1 arc minute of unknown origin were found. Later observations at 1.4 GHz (e.g. Gray et al. 1998; Uyaniker et al. 1998; 1999) discovered similar nulls of polarization intensity with no known total intensity source association. Clearly these were manifestations of Faraday depolarization not known previously. This also meant that RM in Galactic emission was much greater than found by Spoelstra (1984). More recent studies of RM in the continuum emission of the Galaxy (e.g. Gaensler et al. 2001; Wolleben & Reich 2004) suggest much higher values, up to ± 200 rad m^{-2}. It is also interesting to note that the reversals in the sign of RM take place often near H II regions (e.g. Gaensler et al. 2001). Both the Canadian Galactic Plane Survey (CGPS) by Taylor et al. (2003) at 408 MHz and 1.4 GHz and the Effelsberg Medium Latitude Survey (Reich et al. 2004) at 1.4 GHz bring new information. The start of polarization mapping at $\lambda = 6$ cm in both Urumqi (China) and Toruń (Poland) will give crucial new information about the magnetic fields in our Galaxy.

There has been little addition to the data on the RM of EGRS across the sky since the work of Simard-Normandin & Kronberg (1980) who published data on 543 sources. Some additions for limited regions have been made giving us presently data on ∼ 900 sources, but with a very uneven distribution across the sky. A sample of 143 EGRS from the B3–VLA survey were studied by Klein et al. (2003) in the limited declination range. A new survey of 1800 sources is underway in Effelsberg (Han & Reich, private communication). New RM data on EGRS in the Galactic plane became available as a result of the CGPS by Brown (2002) and Brown et al. (2003a). The analysis of the CGPS data showed that there are many local reversals in the Galactic plane (Brown & Taylor 2001; Brown et al. 2003b) most of them associated with H II regions. These observations are in general in the direction of the Galactic anticenter where few pulsars have been detected. However these data have RM values of RM up to ± 1000 rad m^{-2}. The extension of studies of EGRS in the southern plane (J-A Brown, private communication) shows similar large values of RM ± 1000 rad m^{-2}, especially in the direction of the Norma spiral arm. It is obvious that with such high values of RM corrections are necessary for all sources observed through these dense Faraday screens.

Pulsar RM observations were interpreted to show a definite bi-symmetrical structure (Han et al. 1999; 2002) of the magnetic fields in the Galaxy. Han et al. (2002) suggested a magnetic field reversal in an outer spiral arm, beyond the Perseus arm based on rather anomolous values of RM of two objects. Studies by Mitra et al. (2003) of RM of pulsars in the direction of the Perseus spiral arm found that RM reversals can be associated with foreground H II regions. Certainly substantial increase in DM accompanies an eclipse of a pulsar by an H II region. RM results for the local and Persues spiral arms indeed show that the majority of RM results suggest a clockwise magnetic field. In the Sagittarius section of the inner spiral arm there is a reversal suggesting an anticlockwise magnetic field orientation. However there are many points with opposite signs of RM and the trend from the Sagittarius arm does not continue in to the Carina spiral arm. There a mixture of RM directions is observed. Certainly it is most difficult to determine the reasons for the changing values of DM and the sign of RM for distant pulsars. Each line of sight towards the Galactic center passes through many Faraday screens that cannot be easily separated. We must await additional Hα data where the velocities can help us to disentangle the information. Also new methods of data analysis, like the wavelet analysis (e.g. Stepanov et al. 2002), may help us to understand the real structure of the Galactic magnetic fields.

4 Discussion

The combination of all the data discussed above must be used to give us a consistent picture of the morphology of the Galactic magnetic field. The complexity of the data prevent us from describing Galactic magnetic fields in a single unique model. We can however make statements about some hard 'facts' and give some less definite speculations. The 'facts' should guide the theoretical modeling. Some of the 'old' data can be found in Han and Wielebinski (2002). The new data have been discussed at length in the Antalya Proceedings by Uyaniker et al. (2004).

1. Magnetic fields are present everywhere in the Milky Way. They are concentrated in the Galactic plane but also found at high Galactic latitudes.

2. The deconvolution of the low frequency radio continuum data suggests a magnetic field with $B_{total} \sim 10\,\mu G$ near the center of the Galaxy, falling off to values of $B_t \sim 5\,\mu G$ beyond a radius of 15 kpc (see Beuermann et al. 1985)

3. The nulls in polarized intensity seen at 1.4 GHz suggest a deep Faraday screen medium with RM > 35 rad m^{-2} also in the Galactic anticenter direction. The Faraday screens towards the Galactic center show RM jumps of $\pm$ 200 rad m^{-2} on arc minute scales.

4. The new RM data on EGRS shows high values in the Galactic plane, with RM values of up to $\pm$ 1000 rad m^{-2}. This suggests that Faraday depth is dependent on the angular resolution scale.

5. Pulsar RM data are very important in the studies of Galactic magnetic fields but they must be corrected for the foreground effects that may effect the real RM data. Certainly in the direction of the Galactic center the foreground RM can be severe.

6. There is a general clockwise direction of the Galactic magnetic field in the local and Perseus arms. The strong reversal in the direction of the Sagittarius arm is not continued in the Carina arm. Magnetic field reversals are often seen on the edges of Hα/H II regions.

7. The Galactic magnetic field has in general a field strength of $B_{regular} \sim 5\,\mu G$. The random field component has a comparable magnitude, possibly a greater value, i.e. $B_{random} > 5\,\mu G$. (see Beck 2001)

8. The Galaxy must be compared with observations of other nearby galaxies since we cannot expect our Milky Way to have a unique magnetic field structure.

9. All available data must be fitted to model the Galactic magnetic field.

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