

On Large-Scale Magnetic Field Reversals in the Outer Galaxy

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ABSTRACT

We combine the observations of rotation measures of extragalactic radio sources from the Canadian Galactic Plane Survey and pulsars to investigate the question of magnetic field reversals in the outer Galaxy. Our results are consistent with there being no reversal in the Galactic magnetic field beyond the solar radius. We reconcile our conclusions with the results of previous studies that have been used to argue the presence of such reversals.

Subject headings: Galaxy:structure—ISM:magnetic fields—polarization

1. Introduction

A magnetic field reversal is a region of magnetic shear across which the magnetic field direction changes by approximately 180° , corresponding to a slab of current. Identification of these reversals is critical to the understanding of the origin and evolution of the magnetic field in our Galaxy. The two competing interpretations about the origin of the magnetic field (primordial or dynamo) could be distinguished by observing the sequence of large-scale reversals in our Galaxy. A primordial magnetic field, when twisted by the galactic rotation, leads to a bisymmetric field structure. On the other hand, a Galactic dynamo can produce axisymmetric magnetic fields (ex. Sofue et al. 1986; Wielebinski & Krause 1993; Zweibel & Heiles 1997).

One method of detecting reversals is to examine the sign and magnitude of rotation measures (RM) of linearly polarized sources, both Galactic (pulsars) and extragalactic (background galaxies and quasars). The RM is dependent on the magnetic field through the relation

$$\text{RM} \propto \int n_e \mathbf{B} \cdot d\mathbf{l} \quad (1)$$

where n_e is the electron density, \mathbf{B} is the magnetic field, and $d\mathbf{l}$ is an increment of path length through the plasma directed toward the observer. If the thermal electron content is

known along a line of sight, the strength and direction of the line-of-sight component of the magnetic field can be determined. Moreover, since the sign of the RM can only be affected by the direction of the line-of-sight component of the magnetic field, RMs are a powerful tool for probing the topology of the magnetic field.

The direction of the magnetic field in the local arm ($R = 8.5$ kpc) has been inferred from pulsar RMs (Rand & Lyne 1994) and the polarization of starlight in conjunction with the pulsar RMs (Heiles 1996a) to be towards galactic longitude $88^\circ \pm 5^\circ$ and $82.8^\circ \pm 4.1^\circ$, respectively. Thus, as viewed from the North Galactic pole, the local field is directed ‘clockwise’.

Using rotation measures of extragalactic sources (EGS), Simard-Normandin & Kronberg (1979) made the first identification of a magnetic reversal in our Galaxy, occurring approximately 0.5 kpc inside the solar circle at $R = 8.0$ kpc. Lyne & Smith (1989) confirmed this result using pulsar RMs. This reversal indicates that the magnetic field in the Sagittarius-Carina arm is directed counter-clockwise. Further studies by Rand & Lyne (1994) using both pulsars and EGS suggested another field reversal at $R \sim 5.5$ kpc back to a clockwise magnetic field direction in the Scutum-Crux spiral arm. More recently Han et al. (2002) have suggested a counterclockwise magnetic field at $R \sim 3$ kpc in the Norma spiral arm. However, it must be pointed out here that the thermal electron distribution towards the inner Galaxy is very complex and hence complicates these discussions. Both magnetic fields and thermal electrons have a very turbulent structure as can be perceived by studies of polarized radio continuum with high angular resolution (ex. Gray et al. 1999; Uyaniker et al. 1999; Gaensler et al. 2001)

As a consequence of the paucity of available data, identification of reversals beyond the solar circle has been more controversial. Simard-Normandin & Kronberg (1980) tested several magnetic field models and concluded that the observations were consistent with models without reversals beyond the solar circle. Similarly, Vallée (1983) used EGS data and simple models to conclude the Perseus arm possesses a magnetic field directed similar to the local arm. Using this information and dynamo theory, Vallée (1991) predicted that the field in the next arm beyond the Perseus arm should also be directed clockwise.

Conversely, Sofue & Fujimoto (1983) argued for a bisymmetric magnetic field structure in the Galaxy which would imply a field reversal in an outer arm beyond the Perseus arm. Lyne & Smith (1989) presented evidence in support of a reversal in the outer Galaxy, by comparing the RMs of pulsars and EGS. They plotted RM versus dispersion measure (DM) for two regions where pulsar and EGS data were available. For both regions, the magnitudes of RM for the EGS were considerably smaller than the most distant pulsars. They concluded a field reversal beyond the Perseus arm may be the cause of this difference. Using EGS data

confined to two specific directions, Clegg et al. (1992) reinforced the conclusions of Lyne & Smith (1989). In addition, Han et al. (1999) performed a similar study to Lyne & Smith (1989) using newer pulsar data, and arrived at similar conclusions.

In all of these studies, the EGS data were either distributed over large regions of the sky (and not restricted to the Galactic plane where the magnetic field is concentrated), or were very small in number. While the pulsar data were confined to regions nearer to the Galactic plane, the number of objects with determined RM was also small, and foreground effects (eg. H II regions) were not considered. More recently, Brown & Taylor (2001) presented RM data for EGS from the Canadian Galactic plane survey (CGPS) which gives high-density coverage of the sky at low Galactic latitudes towards the outer Galaxy. These new data are not consistent with a reversal between the solar circle and the Perseus arm, and indicate a reversal beyond the Perseus arm is unlikely. Similarly Mitra et al. (2003) used pulsar RM data corrected for foreground effects to show that the proposed reversals in the outer arm from pulsar studies are affected by the presence of foreground H II regions. In this paper, we combine observations from Brown & Taylor (2001) and Mitra et al. (2003), with additional new EGS data to revisit the question of magnetic field reversals in the outer Galaxy.

2. The Data

For our study, we use RM of EGS obtained from the CGPS (Taylor et al. 2003) using the method described in Brown et al. (2003), as well as a subset of the RMs of pulsars from Mitra et al. (2003). The CGPS uses the Dominion Radio Astrophysical Observatory Synthesis Telescope with $1'$ resolution at 1420 MHz to map the Galactic plane in the region $74.2 < l < 147.3$, $-3.6 < b < +5.6$. In addition to the sources published in Brown et al. (2003), we have calculated the RM for an additional 200 CGPS sources in this region, which will be published in a subsequent paper. The large number and high density (roughly 1 source per square degree) of EGS RMs from the CGPS provide a reliable measure of the RM through the disk at low Galactic latitudes, and an estimate of the variation in that quantity over angular scales of a few to tens of degrees.

Mitra et al. (2003) published new RMs for 11 pulsars using observations from the Effelsberg telescope. Combining these with 34 previously measured pulsar RMs, they showed that H II regions between some of the pulsars and the Sun had a significant effect on RMs, leading to anomalously large values. In this study, we consider the RMs of pulsars that are not obscured by H II regions.

3. Analysis

In their studies, both Lyne & Smith (1989) and Han et al. (1999) used the region $105^\circ < l < 135^\circ$, $|b| < 30^\circ$. This longitude range is particularly valuable for studying the outer Galaxy for two reasons. First, it is sufficiently far from the tangent point of the large-scale field, estimated between $160^\circ < l < 180^\circ$ (Vallée 1983), so that the line-of-sight component of the large-scale field is significantly greater than zero, allowing the RMs to probe the Galactic field geometry. Second, RM sources have proportionally larger path-length fractions through the Perseus arm and outer Galaxy than through the local arm, compared to that for lower longitudes. We revisit this region, but instead use only EGS from the CGPS and unobscured pulsars within the latitude range of the CGPS. Figure 1 is a plot of this region in 21 cm continuum total intensity with RM sources over-plotted (262 EGS, 12 pulsars).

In the left panel of figure 2, we show the distribution of RM for the CGPS sources in this region (dark histogram). The majority of the RMs are negative (235 sources), consistent with the average line-of-sight magnetic field directed away from the Sun. As discussed by Mitra et al. (2003), foreground H II regions were seen to correlate with unusually large RMs for pulsars at longitudes near 113° (most notably around CAS A). Figure 1 shows these pulsars superposed on a region of enhanced 21-cm emission. To assess a possible similar bias in the CGPS sources, we calculated the emission measure (EM) along the line of sight to all of the CGPS sources, using the method described in Mueller et al. (2003) in order to identify sources with significant foreground emission. The RM distribution for CGPS sources with foreground EM less than 50 pc cm^{-6} (187 sources) is shown as the light histogram in figure 2. The difference in these two histograms indicates that sources with excess EM are preferentially associated with larger negative RMs, as was observed by Mitra et al. (2003) for the pulsars. However, the mean RM changes only slightly from -147 rad m^{-2} to -121 rad m^{-2} .

Following Lyne & Smith (1989), we plot the RM vs DM for sources in this region (right panel fig. 2), placing the EGS at $DM = 300 \pm 50 \text{ pc cm}^{-3}$. The pulsars are represented by squares. The open squares in the figure indicate pulsars flagged by Mitra et al. (2003) as obscured by H II regions. For those pulsars without error bars, the errors are smaller than the symbol size. The CGPS sources are represented by circles placed at the mean of the corresponding distribution in the left panel, with the vertical error bars representing plus and minus one standard deviation of the distributions. These graphs do not indicate a reversal in the Galactic magnetic field since the RMs are consistent with a monotonic decrease with distance, with the mean magnitude of the CGPS sources (both with and without EM selection) following the trend indicated by the pulsars.

The trend in the right panel of figure 2 lends itself to further speculation about the field in the outer Galaxy. Beck (2001) showed that based on the synchrotron radiation, and assuming energy equipartition between the magnetic field and cosmic ray energy densities, the strength of the total magnetic field should decrease radially in the Galaxy. The radial dependence is expected to be R^{-1} or R^{-2} (Heiles 1996b). We fit the unobscured pulsars and each of the CGPS mean data points with an exponential function of the form $\text{RM} = a_1 - a_1 e^{-\text{DM}/a_2}$ so that the graph is constrained to pass through the point $(\text{RM}, \text{DM}) = (0, 0)$. For this function, a_1 represents the value of RM expected at the edge of the Galaxy (ie. as DM becomes very large), and a_2 is the ‘e-folding’ DM value (ie. the DM value at which RM drops by $1/e$). We note that such a relationship could arise from a situation where both n_e and \mathbf{B} have a R^{-1} dependence. The best-fit parameters are $a_1 = -136 \text{ rad m}^{-2}$, $a_2 = 123 \text{ pc cm}^{-3}$ for the EM limited CGPS data, and $a_1 = -170 \text{ rad m}^{-2}$, $a_2 = 167 \text{ pc cm}^{-3}$ for the unrestricted CGPS data. The data, while limited, are consistent with a radial decay in both the electron density and magnetic field strength with no large-scale reversal in the field direction.

We now consider one region studied by Clegg et al. (1992) that falls within the CGPS. The left panel of figure 3 is a 21-cm continuum emission image of the region centered at $l = 87.5 \pm 3^\circ, b = 0.4 \pm 3^\circ$, with RM symbols over-plotted. The sources that Clegg et al. (1992) used in their study are indicated in white (pulsars are represented by squares and EGS sources are represented by circles), while the CGPS EGS sources are grey. In the same manner as their figure 9b, we plot RM sources versus distance in the right panel of figure 3, with individual EGS placed at 20 kpc. As in figure 2, we also represent the CGPS EGS with one symbol (in grey) at the mean of the RM values in this region ($-356 \pm 372 \text{ rad m}^{-2}$).

From figures 1 and 3, it is evident there is a large variation in RMs on scales of a degree. The two pulsars in figure 3 are separated by more than two degrees. Therefore, the difference in RM between the pulsars is more likely dominated by line-of-sight variation, rather than a radial field dependence. The lower longitude data are also consistent with a monotonic decrease in RM with distance, and evidence for a reversal along this line of sight is not indicated.

4. Summary and Conclusions

With the latest RM data available, we re-examined some of the regions on the sky previously studied for magnetic field reversals. The simplest interpretation of our data is that there is no reversal in the outer Galaxy.

This conclusion is at odds with some previous studies. This discrepancy can be explained by considering the data that was available at the time those studies were conducted. Prior to the CGPS, very few EGS RMs with lines of sight primarily through the Galactic disk were available. For a magnetic field scale height of 1.5 kpc (Simard-Normandin & Kronberg 1980; Han & Qiao 1994) and minimum magnetic radius of 18 kpc (Clegg et al. 1992), EGS with $|b| > 8^\circ$ at $l = 135^\circ$ (or $|b| > 6^\circ$ at $l = 105^\circ$) do not sample the field in the magnetic disk for a significant fraction of the path. Many of the previous studies allowed latitudes up to 30° in order to have a sufficient number of sources in their study. Of the 674 EGS in Broten et al. (1988), the catalog used by Han et al. (1999) and includes the data used by Lyne & Smith (1989), 25 sources have $|b| < 30^\circ$ in the longitude range $105^\circ < l < 135^\circ$ and of these, only 8 have $|b| < 8^\circ$.

Consequently, for many of the previously-measured EGS, the fraction of the line-of-sight path sampling the magnetic disk is less than the path lengths of the pulsars to which they were compared, as illustrated in figure 4. As a result, the RMs of the high-latitude EGS will be smaller than the pulsars, since the halo field and the z -component of the disk field are an order of magnitude lower than the azimuthal component of the disk field (Han & Qiao 1994), and the electron density is much lower in the halo. With the new CGPS data, the studies of Lyne & Smith (1989) and Han et al. (1999) can be taken to confirm the weaker halo field. In addition to the latitude effect, critical details regarding the effect of H II regions on the RMs and DMs of pulsars were not known. Finally, the scale-sizes of RM fluctuations within the disk could not have been estimated with the previous data, as they did not have a sampling density on degree scales.

While there remains the possibility of a field reversal well into the outer Galaxy, the new data does not support the existence of a magnetic field reversal beyond the solar circle. With a conclusion of no reversal, the bisymmetry expected from a primordial magnetic field is not present, thereby supporting a dynamo origin for the large-scale Galactic field.

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REFERENCES

Beck, R., 2001, *Space Sci. Rev.*, 99, 243

- Broten, N. W., Macleod, J. M., Vallée, J. P., 1988, *Ap&SS*, 141, 303
- Brown, J.C., Taylor, A.R., 2001, *ApJ*, 563, L31
- Brown, J.C., Taylor, A.R., Jackel, B.J., 2003, *ApJS*, 145, in press
- Clegg, A. W., Cordes, J. M., Simonetti, J. H., Kulkarni, S. R., 1992, *ApJ*386, 143
- Gaensler, B. M., Dickey, J. M., McClure-Griffiths, N. M., Green, A. J., Wieringa, M. H., & Haynes, R. F., 2001, *ApJ*, 549, 949
- Gray, A. D., Landecker, T. L., Dewdney, P. E., Taylor, A. R., Willis, A. G., & Normandeau, M., 1999, *ApJ*, 514, 221
- Han, J. L., Qiao, G. L., 1994, *A&A*, 288, 759
- Han, J. L., Manchester, R. N., Qiao, G. L., 1999, *MNRAS*, 306, 371
- Han, J. L., Manchester, R. N., Lyne, A. G., Qiao, G. J., 2002, *ApJ*, 570, L17
- Heiles, C., 1996, *ApJ*, 462, 316
- Heiles, C., 1996, *Astron. Soc. Pacific Conf. Ser.* , 97, 457
- Lyne, A. G., & Smith, F. G., 1989, *MNRAS*, 237, 533
- Mitra, D., Wielebinski, R., Kramer, M., & Janssen, A., 2003, *A&A*, 383, 993
- Mueller, P., Mitra, D., & Berkhijsen, E., 2003, in preparation.
- Rand, R. J. & Lyne, A. G., 1994, *MNRAS*, 268, 497
- Sofue, Y. & Fujimoto, M. ,1983, *ApJ*, 265, 722
- Sofue, Y., fujimoto, M., & Wielebinski, R, 1986, *ARA&A*, 24, 459
- Simard-Normandin, M., & Kronberg, P. P., 1979, *Nature*, 279, 115
- Simard-Normandin, M., & Kronberg, P. P., 1980, *ApJ*, 242, 74
- Taylor, A. R., et al., 2003, *AJ*, in press
- Uyaniker, B., Fürst, E., Reich, W., Reich, P., Wielebinski, R., *A&AS*, 138, 31
- Vallée, J. P., 1983, *A&A*, 124, 147
- Vallée, J.P., 1991, *ApJ*, 366, 450

Wielebinski, R. & Krause, F., 1993, *A&A Rev.*, 4, 449

Zweibel, E. G. & Heiles, C., 1997, *Nature*, 385, 131

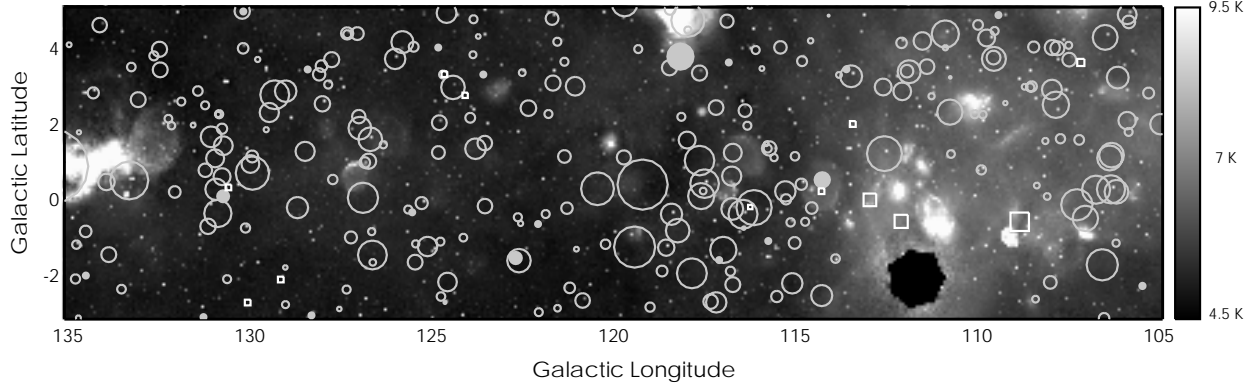


Fig. 1.— Rotation Measure (RM) sources superposed on a 21 cm continuum intensity image from the Canadian Galactic Plane Survey (CGPS) for $105^\circ < l < 135^\circ$. Circles indicate CGPS sources and squares indicate pulsars. Filled symbols represent positive RMs, and open symbols represent negative RMs. Symbol sizes are proportional to the magnitude of the RM and are scaled linearly from $100 - 750 \text{ rad m}^{-2}$. The missing field at $l = 111.5^\circ, b = -2^\circ$ contains the supernova remnant Cas A.

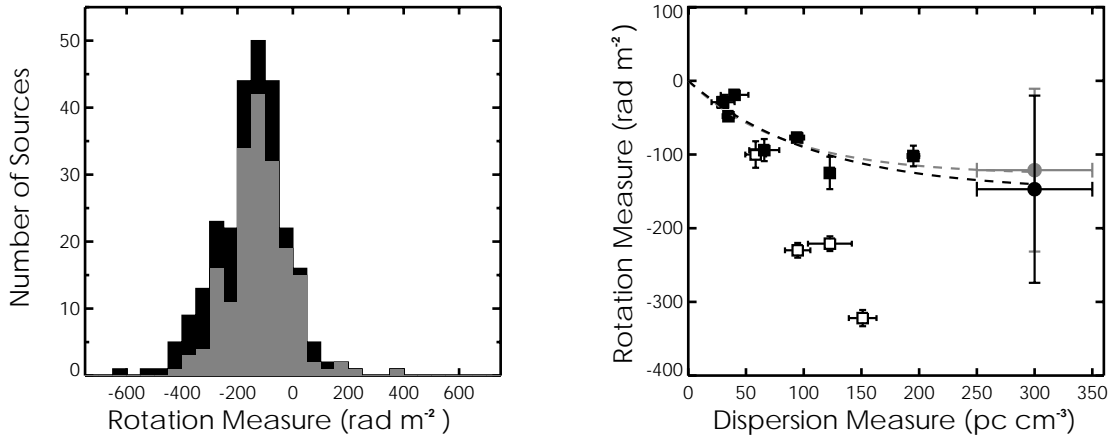


Fig. 2.— Analysis of RMs for the region $105^\circ < l < 135^\circ, -3.6^\circ < b < 5.6^\circ$. The left panel is a histogram of all CGPS RM sources (in black) and of a subset with emission measure (EM) less than 20 pc cm^{-6} (in grey). The right panel is a plot of RM versus dispersion measure (DM) for pulsars (squares) and CGPS RM sources from this region. The light and dark circles correspond to the mean of the distribution of the light and dark histograms respectively, with the error bars indicating one standard deviation. Further details are given in the text.

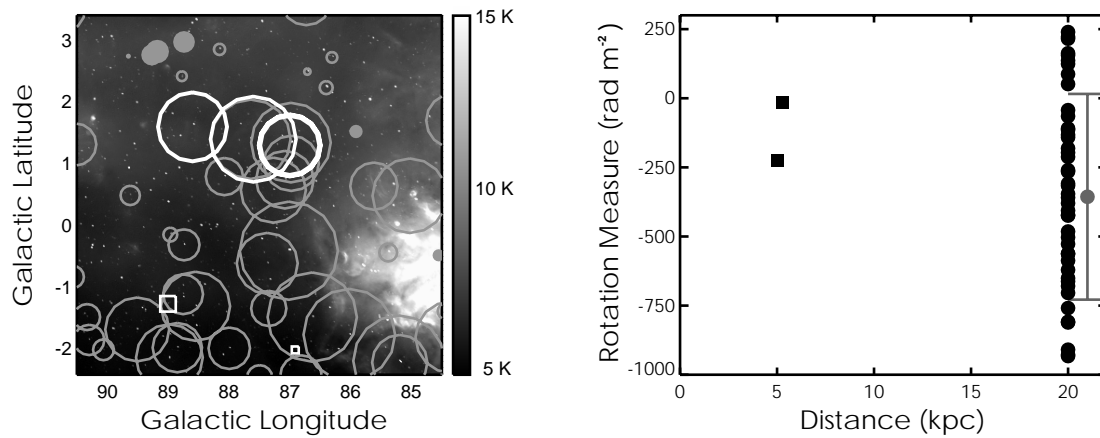


Fig. 3.— Analysis of the region $l = 87.5 \pm 3^\circ, b = 0.4 \pm 3^\circ$. The left panel is the region in total continuum intensity at 1420 MHz. Symbols are as described in figure 1, with white symbols indicating those sources used by Clegg et al. (1992), and grey symbols indicating CGPS sources. The right panel is a graph of RM versus distance after Clegg et al. (1992) figure 9b, with the CGPS sources placed at an arbitrary distance of 20 kpc. The grey symbol with error bars is the mean of the CGPS sources and one standard deviation. Details are given in the text.

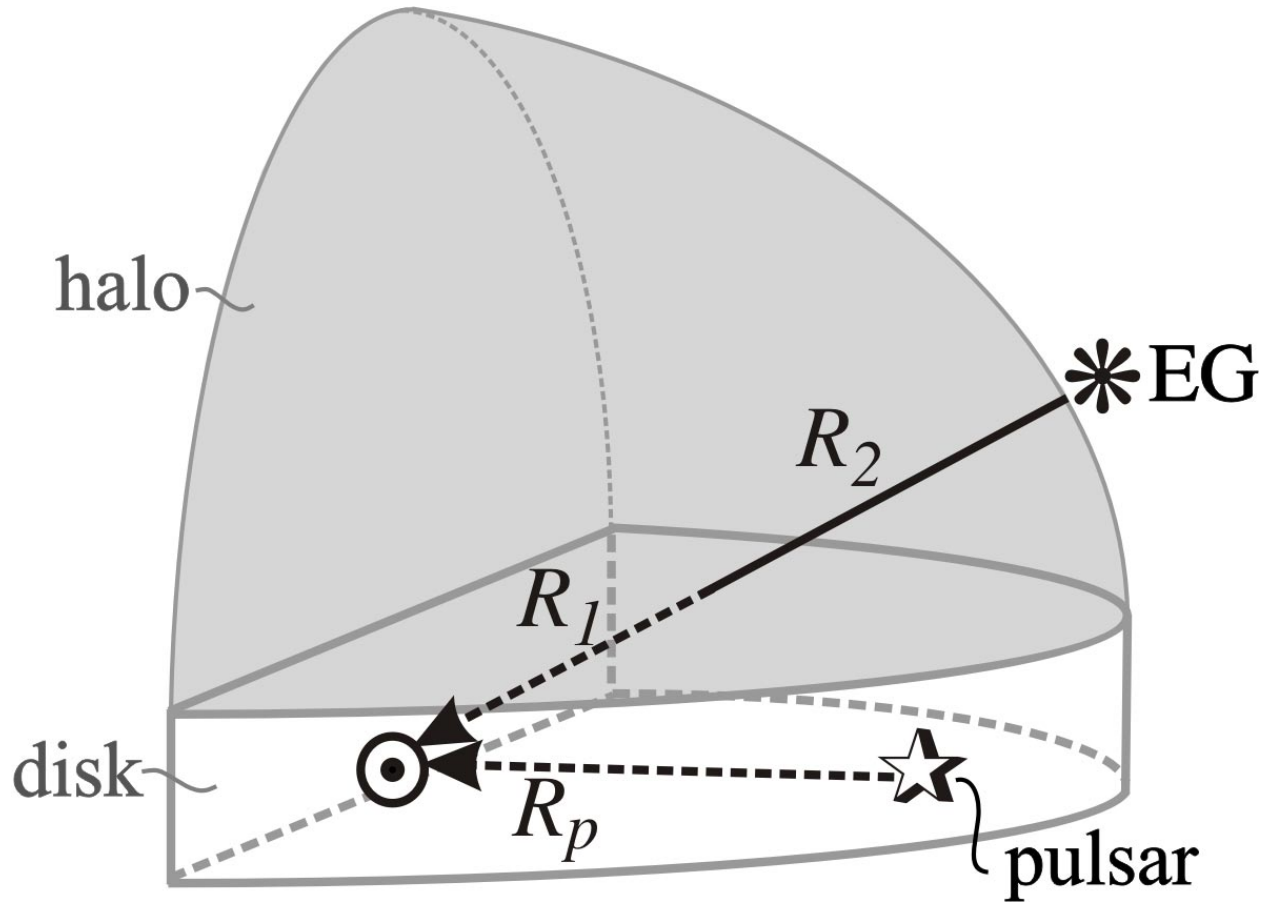


Fig. 4.— Illustration of path contribution differences between a high-latitude extragalactic source (EGS) and a pulsar. In this case, the path length R_1 in the disk for the EGS is less than the path length for the pulsar (R_p).