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Mr. Grote Reber
c/- CSIRO
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Dear Mr. Reber,

Enclosed is a reprint of some recent work I have done on the nonthermal emission from the galactic disk. I hope to look at the question of the local and high latitude structure in the near future. Much of the information for such a study will have to come from the low frequency work you have been carrying out. I will look forward to hearing about the progress you have made on the 1 MHz array and your outlook concerning observations during the current solar minimum.

I enjoyed very much seeing you again last year at Bill Ellis' dinner party. I was especially pleased to hear of your plans for observations at 1 MHz. Your energy and broad range of interests and abilities, both in and out of radioastronomy, have always impressed me very much.

GB-60-133

Enclosed is a photograph which I am sure you will recognize. I have recently discovered it in the archives here at the NRAO and managed to get this copy made for myself. I would be very honored and appreciate very much if you would autograph the photo on the front and return it to me here at the NRAO. Could you also tell me what the "A" on your watch fob (in the picture) stands for?

Thank you for your kindness in responding to this request. I look forward to hearing from you.

With best wishes,

Sincerely yours,

Marc Price

R. M. Price

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Photo

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Best wishes
Marc Price

Continuum Radio Structure of the Galactic Disk

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Summary. An analysis of the 150 MHz continuum profile along the galactic equator suggests that the nonthermal radio emission of the disk has two major components, a base disk and a spiral component. Each contributes approximately one-half of the observed brightness at 150 MHz. The volume emissivity of the base disk decreases with increasing distance from the galactic center. The spiral features have volume emissivities that are at least four times the value of the base disk in the same region. The results of the model suggest that the sun is near the inner edge of a nonthermal spiral feature. If the sun is just within such a feature, the local increase in volume emissivity explains the observed brightness at high galactic latitudes and there is no need for a radio halo.

Key words: spiral structure – continuum radiation – radio halo

1. Introduction

The most conspicuous large-scale feature of the sky at radio wavelengths is the "bright" emission band along the galactic equator. It is generally accepted that this emission is associated with the disk of our own galaxy. Not much is known, however, about the distribution of the nonthermal emission regions in the disk.

From observations at 85 MHz, Mills (1959) suggested that the "steps" observed in the longitude distribution of the brightness temperatures along the galactic equator are associated with the tangential points of the spiral features that lie closer to the galactic center than the sun. Several other authors have attempted to identify sudden increases in the nonthermal component of the radiation in the longitude distribution at higher frequencies (Westerhout, 1958; Komesaroff, 1966; Mathewson *et al.*, 1962).

Renewed investigation of the continuum radio disk structure of our galaxy is suggested by two recent developments. First, radio studies of external spiral galaxies have shown that in some cases there is ordered continuum radio structure in their disks (Pooley, 1969a, b; Mathewson *et al.*, 1972; van der Kruit, 1973a, b; van der Kruit *et al.*, 1972). Second, Burton (1971) has shown that for our own galaxy we must use extreme care in the interpretation of neutral hydrogen data relating to structure within the galacitc disk. The problems that he discusses indicate that it may be difficult to define the distribution of the gas in the galactic disk from neutral hydrogen observations alone.

In the present study I consider the available continuum radio data and the possible base disk and spiral component contributions that might lead to the observed continuum radio brightness distribution along the galactic plane. The results from the Lin-Shu (1967) density wave model are adopted as a basis for the spiral features.

2. Observational Data

The primary data for this study were obtained at a frequency of 150 MHz where the intensity of nonthermal radiation from the disk is much greater than that of thermal radiation. Also, radiation at this frequency does not suffer marked absorption effects in passing through the H II regions of the disk.

Several surveys near 150 MHz and 408 MHz are now available. Table 1 lists the latest and best calibrated of these surveys.

From the studies listed in Table 1 two profiles of brightness temperature along the galactic plane were derived, one at 150 MHz and one at 408 MHz. All of the studies at 150 MHz were carried out on the same telescope (Parkes 64 m), and the telescope parameters of Landecker and Wielebinski (1970) were used for the normalization and conversion to brightness temperatures. The profile was derived from the Whole Sky map of Landecker and Wielebinski (1970), the profiles given in Wielebinski *et al.* (1968), and the map of Hamilton and Haynes (1969). The effective smoothing on the profile is approximately 3°, and individual sources were not removed. The derived profile is shown in Fig. 1.

Using a profile obtained with a resolution of three degrees presents a difficulty. We expect the compression regions to be no thicker perpendicular to the plane than about 200 pc, approximately the half-density thick-

Table 1. Surveys of brightness temperature

Authors	Year	Frequency (MHz)	Angular resolution	Remarks
Wielebinski *et al.*	1968	150	2.2°	Galactic plane profiles, 300° < l < 60°
Hamilton and Haynes	1969	153	2.2°	Southern sky map
Landecker and Wielebinski	1970	150	2 – 5°	Whole sky map
Large *et al.*	1961	400	~0.8°	Northern galactic plane
Seeger *et al.*	1965	400	~2.0°	Northern sky map
Komesaroff	1965	408	0.8°	Southern galactic plane
Price	1970	408	0.8°	Galactic center region and calibration
Haslam *et al.*	1970	408	~0.8°	Anticenter region

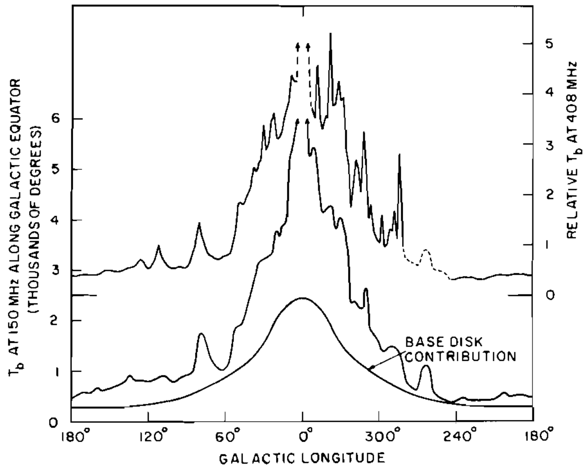

Fig. 1. Profiles of observed brightness temperature along the galactic equator. Upper trace: 408 MHz; lower trace 150 MHz

ness of the neutral hydrogen disk. On the distant side of the galaxy, such a feature would appear only 30′ wide in a galactic latitude. Thus a larger beam or resolution element in the profile would tend to weight the nearby regions more heavily and wash out the effects of the more distant features. But, over the portion of the disk which gives rise to the characteristic profile to be expected from this model (the region where we are essentially looking near tangential points of spiral features interior to the sun) resolution of a few degrees will suffice.

The composite profile at 408 MHz was derived by taking the results of Seeger *et al.* (1965), Large *et al.* (1969) and Komesaroff (1966) and normalizing them by using the baselevel determinations of Price (1970, 1971). The 408 MHz profile shown in Fig. 1 is the brightness temperature along the galactic plane averaged over ± 30′ from $b = 0°$. The effects attributable to the differences in beam sizes in the surveys that were used are small compared with the effects discussed in this paper. The 408 MHz profile shows substantially the same features as that obtained at 150 MHz. Individual sources were not removed.

The 408 MHz profile is shown only for comparison. As expected, its general form is similar to that of the 150 MHz profile. Differences are due largely to effects of resolution between the two surveys, and in some cases, perhaps, to the spectrum of the observed radiation.

In the profiles of brightness temperature *vs* galactic longitude in Fig. 1, three things should be noted. First, there are sudden increases in brightness temperature at approximately 50° and 300° in longitude. At longitudes closer to the center, the brightness temperatures continue to increase irregularly and reach a maximum at the longitude of the galactic center. Second, for longitudes greater than 60° from the center, the brightness distribution is fairly flat. The only obvious large-scale features in these regions are at longitudes 80° and 265°, and in these regions the brightness temperatures are roughly a factor of two higher than those in the rest of the outer regions. Third, there are bumps and irregularities all along the profiles.

It is noted at this point that the regions of higher brightness temperature at longitudes 80° and 265° are not aggregates of sources that are unresolved with the resolution used to obtain Fig. 1. Although there are sources in these regions, the bulk of the brightness temperature is due to extended features. This has been clearly shown in the region at 265° by the 408 MHz survey with the Mill's Cross where the resolution was approximately 3′ (Green, private communication).

3. Interpretation of the Data

a. Base Disk Component

The purpose of the present study is to explain the gross properties of the profiles in Fig. 1 in terms of the large-scale structure of the galactic disk. The basic procedure is to account for as much as possible of the observed emission using as simple a base disk model as possible. The primary restriction on the model is that the contribution from the base disk be less than the observed brightness temperature at all longitudes.

First, consider the concentration of brightness temperature toward the galactic center. The simplest view of this distribution is that it is due to the position of the sun with respect to a galactic disk with nearly constant

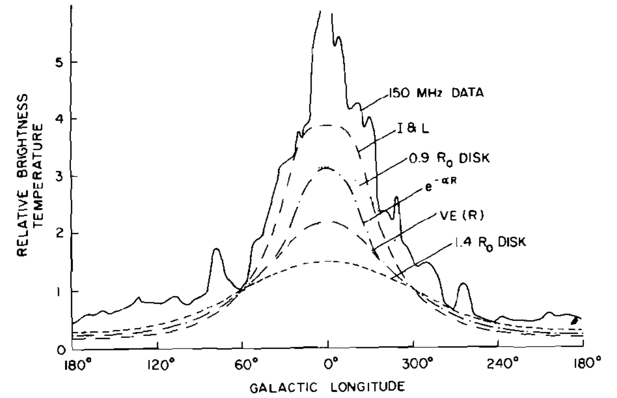

Fig. 2. Profiles of expected brightness temperatures along the galactic equator for various base disk models. I & L uses the Ilovaisky and Lequeux (1972) empirical volume emissivity function. 0.9 R_0 and 1.4 R_0 models assume a constant volume emissivity from $R = 0$–$0.9\,R_0$ and $R = 1.4\,R_0$, respectively, the $e^{-\alpha R}$ and $VE(R)$ models assume volume emissivity falling linearly and as $e^{-\alpha R}$ from $R = 0$–$1.4\,R_0$, respectively. Models are normalized so that at no longitude is the modeled brightness temperature greater than the observed brightness temperature

volume emissivity throughout its extent. The only variables in such a simple model are the radius of the galactic disk, the distance of the sun from the center, and the volume emissivity of the disk. The brightness distribution resulting from a disk of radius $1.4\,R_0$ is shown in Fig. 2. It is clear from the width and shape of this distribution that such a model cannot explain the observed distribution.

Another possibility which has been suggested (Baldwin, 1967) is that the nonthermal disk has a radius of approximately $0.9\,R_0$. Although this possibility cannot be excluded, it seems highly improbable, since it still leaves the emission from the anticenter regions to be explained. Thus far, the high-resolution radio observations of external galaxies do not support such a hypothesis.

The next simplest model is one in which the volume emissivity decreases in some regular fashion from the center to the outer parts of the galaxy. In one such model the volume emissivity falls off linearly as a function of radius. Depending on the rate of falloff (slope) selected, it is possible to obtain a brightness distribution that is strongly concentrated toward the center. The radius from the galactic center at which such a function reaches zero is determined by the slope of the function. For a slope which gives an adequate approximation to the observed concentration toward the center, the brightness contributed at longitudes greater than 120° from the center is small and does not satisfactorily explain the observed brightness distribution along the galactic equator toward the anticenter. The profile resulting from such a model is shown in Fig. 2 as $VE(R)$.

A third function considered was one in which the volume emissivity was proportional to $e^{-\alpha R}$, where R is the distance from the center of the galaxy and α is a scale factor. This function describes the radial luminosity distribution (stellar) in the disks of many spiral systems (de Vaucouleurs, 1959). The scale factor in this function allows adjustment of the degree of concentration to the center obtained in the derived brightness distribution. Figure 2 shows the result with this relationship used, with $1/\alpha$ set equal to 6.0. Since the volume emissivity given by this relationship drops to zero only at infinity, the disk was arbitrarily truncated at $1.4\,R_0$.

Ilovaisky and Lequeux (1972) (I & L) have derived an empirical volume emissivity function to fit the observations. It was designed to account for most of the emission observed from regions of the disk closer to the galactic center than the sun. Its contribution was also truncated at $1.4\,R_0$.

The radius at which the $e^{-\alpha R}$ and the I & L models were truncated has very little effect on the shape of the resulting brightness profiles along the galactic plane. But it does change the zero level, i.e., the contribution that is nearly constant at all longitudes. This is very important in the regions greater than ~90° in longitude from the galactic center. Either of these models would provide a better fit to the anticenter region observations if they were extended to 1.6 or $1.8\,R_0$. It is unlikely that there is any significant contribution to the disk emission from greater than $2.0\,R_0$.

From Fig. 2 it can be seen that at all longitudes the Ilovaisky-Lequeux model and the exponential model give the best fits to the data.

b. Spiral Component

In the preceding Section I sought to account for as large a base disk component as possible within the observed brightness distribution without leaving negative residuals. The residuals (observed minus modelled brightness temperatures) obtained by using the Ilovaisky-Lequeux model and the exponential model are given in Fig. 3. This distribution could be made up of contributions from sources randomly distributed in longitude, sources that are ordered in their distribution in the galactic disk (that is, in spiral features), or effects in the brightness distribution which might be attributed

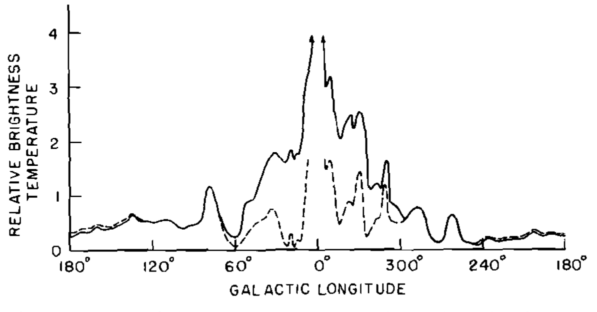

Fig. 3. Residual brightness temperatures ($T_{\text{obs}} - T_{\text{model}}$) using two different base disk volume emissivity models. Solid line: $e^{-\alpha R}$ base disk; dashed line: base disk suggested by Ilovaisky and Lequeux (1972)

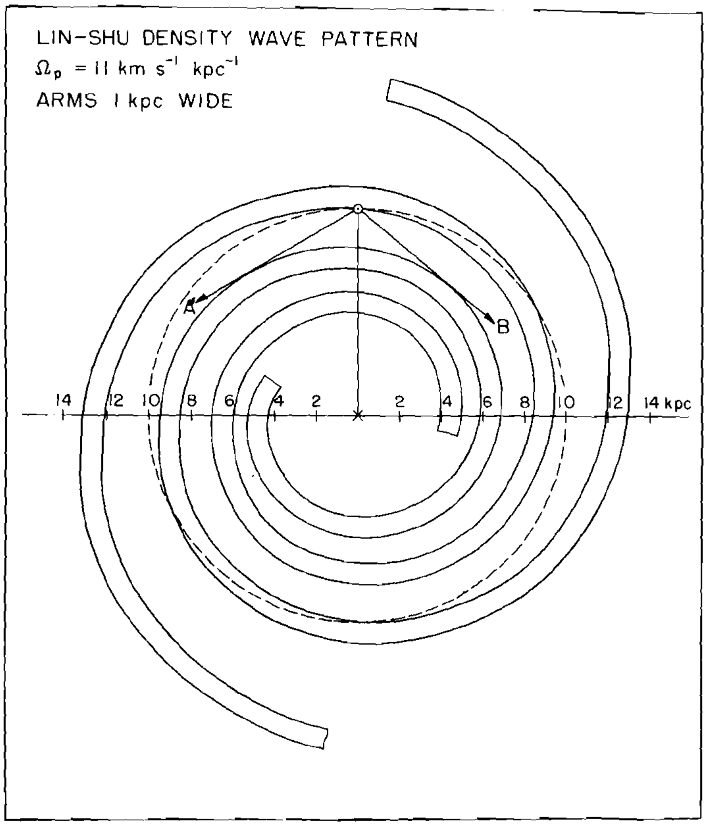

Fig. 4. Model of spiral feature "windows". The form follows the spiral of the Lin-Shu (1967) density wave model

to large-scale ordered regions of enhanced continuum radio emission in the disk, i.e., nonthermal spiral features. In Fig. 3 a simple dependence on galactic longitude is not obvious, but there is a concentration of brightness in regions less than approximately 60° from the center for the residual from the exponential disk model (as shown by the solid curve). The presence of bumps or steps in this residual profile suggest the possibility of contributions from large-scale features.

At the time that Mills (1959) first suggested a contribution from spiral features there was no firm theoretical basis on which a model for comparisons with observed data could be constructed. We now have the spiral density wave theory developed by Lin and his collaborators (Lin and Shu, 1967). It seems appropriate to use this density wave model as a basis for present comparisons.

For the continuum radio emission model shown in Fig. 4, I assume that the spiral features are of constant width, 1 kpc, throughout the galactic disk. This does not mean that we might expect to find continuum radio emission over the entire width of 1 kpc. Roberts (1969) and Roberts and Yuan (1970) have developed the nonlinear density wave theory, including the effects of the galactic magnetic fields. Their models of the two-armed spiral shock pattern predict a density compression with a half-density width in the plane of approximately 200 pc. We know from observations of M 51 that nonthermal radio features do not necessarily follow a smooth pattern but can wander about some mean spiral pattern. Thus, the 1 kpc wide regions define a "window", a range within which we might expect to find the spiral feature. Using a window (for the spiral features) with a width of 500 pc does not change the general form of the expected profile substantially. It causes the peaks due to looking tangentially on along the arms to become narrower.

The shock strength along the spiral features is assumed to be constant. The work of Roberts and Yuan (1970) predicts a reduction in shock strength of nearly two in going from a radius of 4–11 kpc. However, for the present model, which is not meant to be rigorously quantitative, the simplifying assumption of constant shock strength is made. It is also noted that the radio observations of M 51 show that the brightness temperature along spiral features varies (by a factor of 2) about the mean brightness temperature (which does decrease) in going from the center to the outer parts of that galaxy. The effect of this assumption is to give a rather higher weight to spiral emission regions in the outer portions of the galaxy. These are regions in which the form of the base disk distribution is also not well defined.

The emission from the spiral features is assumed to be isotropic. This point was first discussed in detail by

Hanbury Brown and Hazard (1960). They showed that if the magnetic fields were aligned along the spiral features, because of the beaming of the synchrotron radiation (with the maximum emission perpendicular to the field lines) the observed profile along the galactic equator would be more concentrated to the center and would not show the well-defined peaks or bumps which appear when the emission is isotropic. (In the isotropic case the peaks are due to the geometric effect of having long lines of sight along spiral features where we look just interior to their tangent points.) The justification for this assumption will be discussed in the final section of this paper.

Hanbury Brown and Hazard also discussed the effects on the expected profiles of irregularities in the magnetic fields. Irregularities make the emission more isotropic. (Here it is assumed that the scale of the irregularities is small compared to that of the overall spiral feature. In fact, we know little of the magnetic field structure within our galaxy, but Faraday rotation measurements indicate that there are small-scale field irregularities in some directions. It seems a reasonable assumption that irregularities exist on a scale of several hundred parsecs.) The goodness of the fit of a model constructed assuming isotropic emission can be an indicator of the structure of irregularities in the magnetic field within the disk.

Finally, I do not assume any contribution from the spiral component inside of approximately 4 kpc (the inner Lindblad resonance). From observation of external galaxies it is known that the centers of galaxies are often anomalous radio emission regions and this region is not considered in the present study.

To determine the brightness temperature longitude profile, I selected the position of the sun in the spiral pattern and calculated the variation of length of the line of sight intersecting the spiral features as a function of galactic longitude. Since I assumed that the shock strength is constant along the spiral pattern, it was necessary to scale the volume emissivity factor along the arms only as a function of their distance from the center of the galaxy (in the same way as the volume emissivity of the base disk varied).

This model is sensitive to the position of the sun with respect to the local spiral features. First, the longitudes at which the brightness starts to increase substantially depend on the angle subtended, in longitude, by the closest interior spiral feature. Second, the positions and amplitudes of the bumps at longitudes approximately 80° and 260° depend strongly on the position of the sun with respect to the local spiral feature. These effects are shown clearly in Fig. 5. The distribution in Fig. 5 that most closely approximates the residual obtained by using the exponential disk results from placing the sun just at the inner edge of the local spiral feature.

The agreement between residuals obtained by using the exponential base disk model, and the brightness distribution from the spiral features suggests a significant contribution from nonthermal spiral features to the brightness distribution seen along the galactic equator. There is not complete and detailed agreement, and from our knowledge of the patchiness of the spiral structure in external systems, we would not expect it. This simple model has not included spurs, cross links, or connecting regions between the spiral features which are also known to be present in spiral galaxies. Finally, it is also known from the spiral radio distribution observed in external galaxies that the actual volume emissivity can vary greatly along a spiral feature.

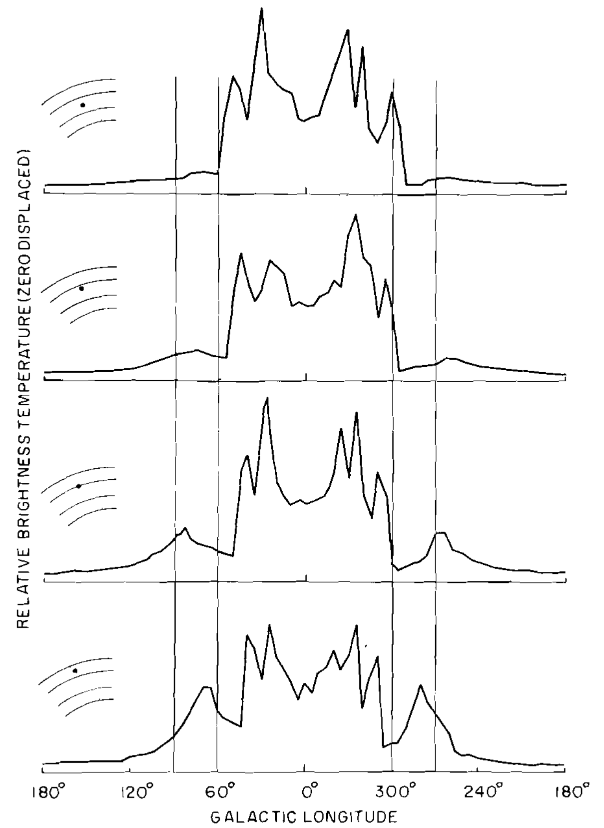

Fig. 5. Brightness temperature contribution expected from spiral nonthermal components for four positions of the sun relative to the two nearest spiral features. Position of sun is indicated by the dot in the figures to the left of each profile

The present study does not include the effects of discrete sources on the observed brightness distribution. If the sources in the galactic plane were located primarily in the spiral features, the effect would be similar to the case in which volume emissivity is smoothly distributed along the spiral feature. A previous study by Mathewson *et al.* (1962) did not indicate a strong tendency for nonthermal galactic sources to clump at longitudes that are believed to be tangent directions for spiral features. More recent high-resolution studies by Green and Mills (private communication) have not shown a large degree of clustering of sources along the galactic equator.

4. Results and Conclusions

There is no compelling observational or theoretical basis on which to prefer the Ilovaisky-Lequeux volume emissivity function over the exponential form suggested here (or vice versa). Considering the simplicity of the model, there is surprisingly good agreement between the observed brightness distribution along the galactic plane and that expected from the exponential base disk plus spiral component model. A comparison of the brightness distribution derived for the base disk emission along the plane and the contribution from the spiral components shows that there is approximately the same amount of power in both of these components. A comparison of the contribution from the disk to the contribution from the spiral features indicates a lower limit of 4:1 in the ratio of volume emissivity in the spiral features to that in the general base disk. This ratio will increase depending on the actual width of the nonthermal spiral features relative to the assumed width of 1 kpc. The narrower the features, the higher the ratio. For instance, if the nonthermal emission regions are only 200 pc in width, the corresponding ratio will be 16:1. This would imply an average density compression of approximately three over the region.

The observed positions of the maxima near 80° and 265° indicate that the sun is near the inner edge of the local nonthermal spiral feature. This idea is supported by agreement in the longitudes at which the inner feature begins to make a significant contribution to the observed brightness, that is, the angle to the tangent points of the nearest inner feature. This would mean that the sun is at the inner edge of the local density wave compression, which itself is displaced inward from the major optical spiral feature.

If the sun were located within the local spiral feature, the higher value of the local volume emissivity would result in higher expected brightness temperatures at high galactic latitudes. This would eliminate the need for a large-scale radio halo to explain the observed high latitude brightness temperatures.

The agreement between the modelled and observed profile along the galactic equator and in particular the observed higher brightness temperatures at longitudes 80° and 265° indicate that the assumption of isotropy in the emission from the spiral features was justified. Further investigation, using a more detailed model might yield estimates of the degree of alignment between the magnetic fields and the structure of the irregularities in the fields.

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