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Modeling Galactic Synchrotron Absorption Measurements in the HII region behind the Galactic center

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We investigate the effect of additional cosmic-ray electron (CRE) sources on the Galactic synchrotron emission distribution along the line of sight (LOS) through the Galaxy. In this way, we try to explain the differences between low-frequency synchrotron measurements and predictions from current Galactic magnetic field and CRE models. We use stochastic differential equations to describe electron CR propagation in the Galaxy. These specific CRE density models are used to simulate synchrotron emissivity at low radio frequencies. We consider individual young supernova remnants as additional sources of CREs, as well as an enhanced CRE density in an extended ring in the outer Galaxy. We compare the observed low-frequency synchrotron emission in the direction of optically thick HII regions with synchrotron emission as predicted by these models. We found that neither a single supernova remnant emitting CRE in addition to the Galactic CRE background, nor additional CREs emitted in a spiral arm, can explain current discrepancies between low-frequency observations of synchrotron emission in the direction of optically thick HII regions. This indicates the need for other solutions to bring synchrotron data in agreement with CRE and GMF models.

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1. Introduction

The interstellar medium (ISM), filled with a dilute mixture of magnetic fields, cosmic rays (CRs), gas and dust, plays a crucial role in many areas of astronomy. It is a crucial part of the Galactic ecosystem as it makes key contributions to the many different processes in the Milky Way [1]. The Galactic Magnetic Field (GMF) interacts strongly with the other ISM components, so that it is essential for understanding of the ISM [2]. A number of analytical models have been published in recent years on the GMF, see for instance refs. [3–7].

During propagation Galactic CR (GCR) interact with magnetic fields. This interaction produces the synchrotron radiation that dominates the radio spectrum at low radio frequencies. However, the origin, acceleration and propagation mechanisms of Galactic CRs are not yet completely understood. GCRs are generally believed to be originated in supernova remnants (SNRs), produced in diffusive shock acceleration up to PeV energies, see for instance [8].

A unique observational tracer of the GMF is the use of free-free absorption of HII regions below 100 MHz, see for instance [9] and [10]. In this method the free-free absorption that occurs at low radio frequencies in Galactic HII regions is used to measure Galactic synchrotron emission either in front of or behind the HII regions. Refs [11, 12], hereafter P19 and P20 respectively, used GMF models and CR density models to predict emissivities integrated over the line-of-sight (LOS) behind Galactic HII regions in the Galactic longitude regime between $-30^\circ < \ell < 5^\circ$. An extensive explanation of the theory of this tracer can be found in P20.

P20 suggests several ways in which the discrepancy between observations and the global models can potentially be solved. In this work we investigate one of these possible solutions. The method we choose, is the introduction of additional synchrotron radiation emitted in the LOS behind HII regions. We test this by adding additional CRE sources in regions of the Milky Way behind these HII regions.

2. Models used

2.1 Galactic Magnetic Field model

We use the GMF model of [5, 6], hereafter JF12. In this work we only consider the magnetic field in the plane of the Milky Way, or the disk component, of JF12, and neglect any vertical magnetic field component. The reason for this is that a vertical magnetic field component would transport the Galactic CREs out of the plane too fast for our models. This approximation is reasonable for large Galacto-centric radii, the Solar circle and beyond, where the vertical field may be much smaller than it is closer to the Galactic Center. In fact, several studies find a small or negligible local vertical magnetic field component at the Solar circle [13, 14]. The easiest way to measure this is by measuring rotation measures (RMs) from extra-galactic sources near the Galactic poles, where a non-zero average RM would indicate a non-zero vertical magnetic field.

2.2 The distribution of cosmic ray density models

In this section we describe the distribution of the CRE density that gives additional CRE sources, to remedy the dearth of synchrotron emissivity in the models, as presented in P20. For this we need extra sources that provide additional CREs in the region behind the farthest HII regions:

behind 10 kpc beyond the Galactic center in the Galactic longitude regime between $-30^\circ < \ell < 5^\circ$. This will likely also enhance the emissivities in the direction of nearby HII regions, but less so than those of the far HII regions due to the shorter path lengths.

We can consider two different source approaches modeled as follows:

1. From a single point source that injects CRs impulsively in the mid-plane ($z = 0$) of the Galactic disk at a fixed Galacto-centric radius close to that of the Sun ($R_\odot = 8.5$ kpc). The emission from this additional CRE source is in excess of the smooth, global emission due to the age $10^4 - 10^5$yr. A single source can indeed, in first order approximation, be a significant contributor to this background as long as it is younger than $\sim 10^5$yr .

   We have simulated the propagation for CRE sources that are located at different locations in the Galaxy, see Table1 for exact locations.

2. We consider the diffusion of CRs originating from multiple sources in a fixed interval in Galacto-centric radius. In this case CRs originate in a ring in the mid-plane of the Galactic disk, centered on the Galactic Center. We distribute the source locations uniformly and randomly in a ring around the Galactic Center, with cylindrical injection radius $r_{\rm inj}$ in the interval 10 kpc $< r_{\rm inj} \leq 12$ kpc. The distribution in cylindrical radius $r_{\rm inj}$ is obtained for each injected particle from the simple prescription:

$$r_{\rm inj} = \sqrt{(r_{\rm max}^2 - r_{\rm min}^2)\ \Xi + r_{\rm min}^2}\ , \tag{1}$$

   where the two radii $r_{\rm min}$ and $r_{\rm max}$ are the inner and outer radius of the ring and Ξ is a random variable distributed uniformly between 0 and 1. The azimuthal angle ϕ of the injection site is chosen randomly from a uniform (top-hat) distribution between 0 and 2π. For a detailed description of the model see [15, 16].

We have run simulations for two different value of the ratio $\epsilon \equiv D_\perp/D_\parallel = 0.01, 1$ for the case of anisotropic diffusion (the CRE propagation tends to follow the spiral disk field) and isotropic diffusion (where the magnetic field has no influence), respectively. The total number of simulated CREs in this work is 4×10^5.

We consider only young SNRs with age $t_{\rm max} \simeq 10^4$ yr as a source of freshly accelerated CREs. This age is much smaller than the typical residence time of CREs in the Galaxy, which is $t_{\rm res} \simeq 10^7$ yr, see for instance [8]. This means that most of the CRE produced in these sources are still diffusing in the Galaxy.

3. Method

We perform this work based on the method and results from P19 and P20. For every HII region line of sight in the P20 catalog we have calculated the excess synchrotron brightness temperature that these added sources would give from simulations. Using the GMF model and the CRE models we calculated the observable synchrotron emission from each LOS towards an HII region with the

#	Coordinates (kpc)	ϵ
1	(0,16)	0.01
2	(0,16)	1
3	(-6,14)	0.01
4	(-6,14)	1
5	(4,11)	0.01
6	(4,11)	1
7	(-5,12)	0.01
8	(-5,12)	1
9	(8,13)	0.01
10	(8,13)	1
11	Ring 10-12 kpc	0.01
12	Ring 10-12 kpc	1

Table 1: Cosmic ray density model locations in the disk of the Galaxy, where (0,0) kpc is the Galactic Centre. The Earth is located at (0,-8.5) kpc. Column (1) has the numerical designation of the different CR models, column (2) shows the coordinate location in kpc for the CR source and column (3) is the ratio of diffusion coefficients for each source location.

Hammurabi code [17]. Hammurabi allows calculation of the synchrotron brightness temperature along the whole line of sight through the Milky Way, or up to a certain distance from the Sun.

Therefore, for each LOS, first the foreground and the total brightness temperature are calculated, which are the brightness temperature integrated over the path from the observer to the HII region (T_F) and the brightness temperature integrated over the LOS path between the Sun and the edge of the Milky Way (T_T), respectively.

The background brightness temperature, i.e. the emission integrated over the path between the HII region and the Milky Way edge, for each LOS can be calculated by subtracting the former from the latter ($T_B = T_T - T_F$). Then we compute the synchrotron emissivity for a LOS by dividing the synchrotron brightness temperature by its companion path length:

$$\epsilon_{\mathrm{B}} = T_{\mathrm{B}}/D_{\mathrm{B}}. \tag{2}$$

where ϵ_{B} is the 'emissivity' along the LOS behind the HII region, defined as the brightness temperature emitted per unit path length in units of K pc^{-1}.

4. Results

The location of the 5 modeled single CRE sources is shown in Fig.1. In the left panel the CREs have propagated isotropically ($\epsilon = 1$), where the magnetic field has no influence. In the middle panel the CREs have been propagated anisotropically ($\epsilon = 0.01$), the distribution shows the CRE propagation tends to follow the spiral disk field. Lastly, a ring of SNRs between 10 kpc and 12 kpc from the Galactic center has been created and CREs for these sources have been propagated with both isotropic (blue) and anisotropic (orange) diffusion, as shown in the right panel. Only 6 models

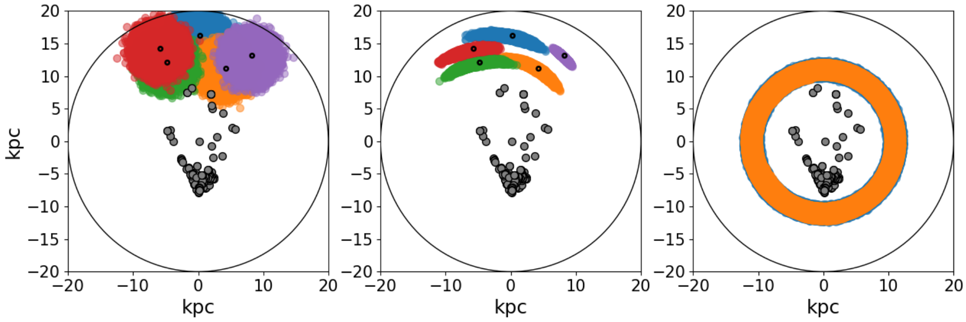

Figure 1: Locations of CREs in each CRE models after isotropic and anisotropic propagation. Left panel: isotropic propagation from the sinlge sources numbered 2, 4, 6, 8 and 10 correspond to the colors blue, red, orange, green and purple, respectively. The middle panel: anisotropic propagation from the sinlge sources numbered 1, 3, 5, 7 and 9 correspond to the colors blue, red, orange, green and purple, respectively. The right panel: the two ring models propagated anisotropically in orange, on the top of the isotropically propagated CREs in blue. The catalog HII regions are plotted in gray filled circles and the location of each of the single sources is indicated with black circles on the CRE distribution. The Sun is located at coordinates (0,-8.5) kpc.

(1, 2, 5, 6, 11 and 12) diffuse enough to show any emissivity enhancement for the far HII regions, see Table.1.

The normalized simulated emissivities are shown in Fig.2. This figure shows only the emissivity from our additional CRE sources added to the emissivity as calculated from the JF12b GMF model [18] and the z10LMPDE CRE model from Galprop [19]. The emissivity in the models is normalized to the observed emissivity with a least-squares minimization.

It is clearly seen that the models follow the data fairly well for long path lengths, i.e. HII regions near the Sun (on the left side of Fig.2). For the short path lengths, i.e. in the far Galaxy behind the Galactic center (on the right side of the figure between the 12-18 kpc path lengths), there is a large discrepancy between the models and the data.

As expected, the emissivities at short path lengths increase more than those at long path lengths. Also, the single-source models with isotropic diffusion have slightly more enhanced emissivities than those with anisotropic diffusion. The fit of the models to the data improves with the additional CRE sources. However, The single-source models only enhance the emissivities at very specific path lengths corresponding to a narrow longitude range over which the single-source CREs are distributed: the particles do not diffuse far enough to cover the longitude range, specifically that of the far HII regions, over which the discrepancy between models and observations exists. Therefore, CREs from a single young supernova remnant cannot solve the discrepancy between the models and the observations.

On the other hand, the ring models do show promising improvement. Their emissivities reveal an improved fit in path lengths $\gtrsim$ 16 kpc, but cannot explain the observations at shorter path lengths. Note that the very low emissivities at the smallest path length bin are in part an artefact of the model:

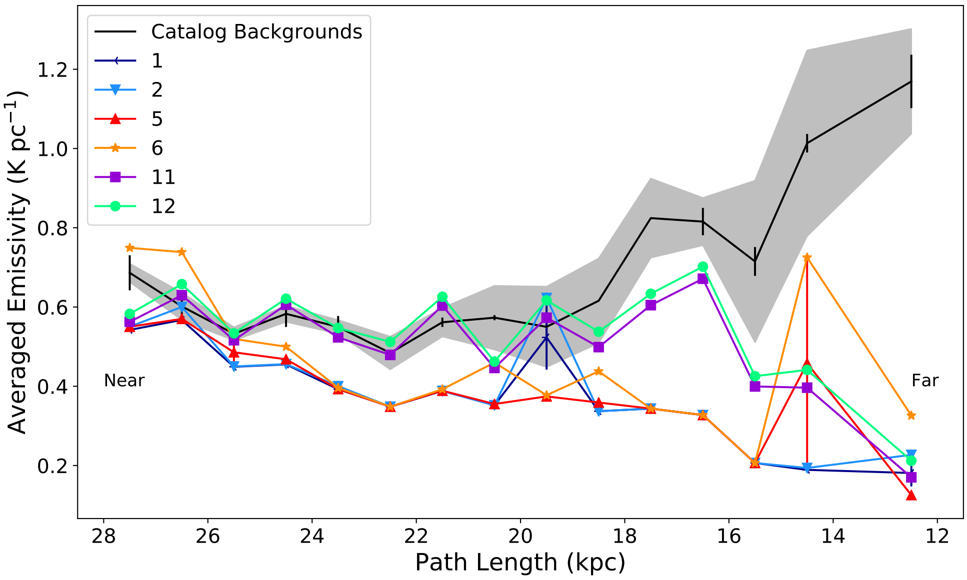

Figure 2: Normalized simulated emissivities for 6 separate sources. The anisotropic models are shown in dark blue crosses for the single source model number 1; red triangles for the single source model number 5, and green dots for ring model number 12. The isotropic models are shown in blue triangle for model number 2, orange stars for model number 6 and purple squares for ring model number 11. The data have been binned in 1 kpc wide bins. The catalog data is shown as a black line with the measurement error plotted as the gray area around it, the black error bars are the standard deviation of each bin.

at these far distances, HII regions are in fact fairly high above the plane where there are few CREs. This is a side effect of turning off the vertical magnetic field component in the CRE diffusion modeling. As a simple test of whether allowing the CREs to diffuse higher resolves the discrepancy with the data, we simply extended the CRE distribution into a thicker disk to ensure that the highest HII regions have the same CRE density as those in the disk (which is very likely an overestimate of their density there).

5. Summary and conclusions

In this work, we investigate the effect of additional CRE sources on the Galactic synchrotron emission distribution over LOS through the Galaxy. We modeled the cosmic ray propagation using stochastic differential equations, solving these numerically. We computed first the expected synchrotron emission in the Galaxy using the Galactic magnetic field model, cosmic ray electron density model and the additional cosmic ray sources. Then, we calculated the expected synchrotron emissivity, defined as synchrotron emission per unit path length, in the direction of the available observational low-frequency synchrotron data towards optically thick HII regions.

We found that it is not possible completely to explain the existing discrepancy between global models and the low-frequency radio observations. Neither the single supernova remnant emitting CRE in addition to the Galactic CRE background, nor additional CREs emitted in a spiral arm, can explain current discrepancies between low-frequency observations of synchrotron emission in the direction of optically thick HII regions. This indicates the need for other solutions to bring synchrotron data in agreement with CRE and GMF models. One possible solution is to look into the existence of a region around the Galactic center - between the near and far HII regions - that shows a paucity of CRE density. This paucity could cause the emissivities for near HII regions to lower, hereby resulting in a trend that can be comparable to the catalog trend.

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