

H I spin temperature in the Fermi-LAT era

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The diffuse high-energy gamma-ray emission of the Milky Way arises from interactions of cosmic-rays (CRs) with interstellar gas and radiation field in the Galaxy. The neutral hydrogen (H I) gas component is by far the most massive and broadly distributed component of the interstellar medium. Using the 21-cm emission line from the hyperfine structure transition of atomic hydrogen it is possible to determine the column density of H I if the spin temperature (T_S) of the emitting gas is known. Studies of diffuse gamma-ray emission have generally relied on the assumption of a fixed, constant spin temperature for all H I in the Milky Way. Unfortunately, observations of H I in absorption against bright background sources has shown it to vary greatly with location in the Milky Way. We will discuss methods for better handling of spin temperatures for Galactic diffuse emission modeling using the Fermi-LAT data and direct observation of the spin temperature using H I absorption.

I. INTRODUCTION

The diffuse Galactic emission (DGE) arises from interactions of cosmic-rays (CRs) with interstellar gas and radiation field in the Galaxy. Due to the smooth nature of the interstellar radiation field and the CR flux after propagation, the fine structure of the DGE is determined by the structure of the interstellar gas. Getting the distribution of the interstellar gas correct is therefore crucial when modeling the DGE.

It is generally assumed that Galactic CRs are accelerated in interstellar shocks and then propagate throughout the Galaxy (see e.g. Strong et al. 2007, for a recent review.). In this paper, CR propagation and corresponding diffuse emission is calculated using the GALPROP code (see Strong et al. 2004, and references within.). We use the so-called conventional GALPROP model (Strong et al. 2004), where the CR injection spectra and the diffusion parameters are chosen such that the CR flux agrees with the locally observed one after propagation. The gas distribution is given as Galacto-centric annuli and the diffuse emission is calculated for those same annuli. The distribution of H I is determined from the 21-cm LAB line survey (Kalberla et al. 2005) while distribution of molecular hydrogen, H_2 , is found using the CO ($J = 1 \rightarrow 0$) survey of Dame et al. (2001) assuming $N_{H_2} = X_{CO}(R)W_{CO}$.

While converting observations of the 21-cm H I line to column density is theoretically possible, it is not practically feasible. To correctly account for the optical depth of the emitting H I gas, one must know its spin temperature, T_S (see e.g. Kulkarni and Heiles 1988). Under the assumption of a constant T_S along the line of sight, the column density of H I can be calculated from the observed brightness temperature

T using

$$N_{HI}(v, T_S) = -\log\left(1 - \frac{T}{T_S - T_{bg}}\right) T_S C, \quad (1)$$

where T_{bg} is the background continuum temperature and $C = 1.83 \times 10^{18} \text{ cm}^{-2} \text{ K (km/s)}^{-1}$. The assumption of a constant T_S along the line of sight is known to be wrong for many directions in the Galaxy (see e.g. Dickey et al. 2009). The T_S values derived in this paper are therefore only a global average and should not be taken at face value. Figure 1 shows how changing T_S affects N_{HI} in a non-linear way, mainly affecting areas with T close to T_S in the Galactic plane. This figure was created under the assumption of a fixed T_S for the whole Galaxy that is known to be wrong but has been used for DGE analysis from the days of COS-B (Strong 1985). Note that for equation (1) to be valid the condition $T_S > T + T_{bg}$ must hold. When generating the gas annuli, this condition is forced by clipping the value of T .

While the assumption of a constant spin temperature $T_S = 125 \text{ K}$ for the whole Galaxy may have been sufficient for older instrument, it is no longer acceptable for a new generation experiment like Fermi-LAT (Atwood et al. 2009). This has been partially explored for the outer Galaxy in Abdo et al. (2010a). In this paper we will show a better assumption for T_S can be easily found and also show that direct observations of T_S using absorption measurement of bright radio sources are needed for accurate DGE modeling.

II. METHOD

We assume the source distribution of CR nuclei and electrons are the same. CR propagation is handled

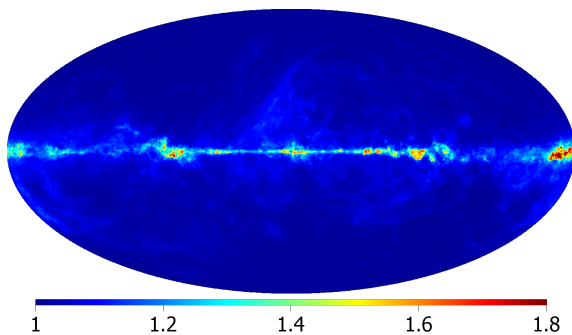


FIG. 1: The ratio $N_{HI}(125\text{ K})/N_{HI}(200\text{ K})$ in Galactic coordinates. The figure clearly shows the non-linearity of the correction that can be as high as a factor of 2 in this case.

by GALPROP and we use the conventional model so that after the propagation the CR spectra agree with local observations. The GALPROP diffuse emission is output in Galacto-centric annuli, split up into different components corresponding to different processes (bremsstrahlung, π^0 -decay, and inverse Compton scattering). To allow for radial variations in CR intensity we perform a full sky maximum likelihood fit, preserving the spectral shape of each component. We allow for one global normalization factor for the electron to proton ratio. Additionally, we also allow for radial variation in the X_{CO} factor. This accounts for uncertainties in the CR source distribution and X_{CO} factor.

The maximum likelihood fits were performed on the whole sky using the GaRDian package (Abdo et al. 2009) after preparing the Fermi-LAT data with the science tools. We use the same dataset as Abdo et al. (2010b) that has special cuts to reduce CR background contamination compared to the standard event selection (Atwood et al. 2009). In addition to the DGE model, we also include all sources from the 1 year Fermi-LAT source list (Fermi LAT collaboration 2009) and an isotropic component to account for EGB emission and particle contamination. This fit is performed for different assumptions of T_S and a likelihood ratio test is used to compare the quality of the fits.

III. RESULTS

The simplest assumption is that of a constant T_S for the whole Galaxy and it deserves some attention for historical reasons. It will also serve as a baseline model for comparison with other assumptions. To get an approximation for the best model, we scan T_S from 110 K to 150 K in 5 K steps. Our results show that $T_S = 130\text{ K}$ gives the maximum likelihood for this setup.

One of the problems with the constant global T_S

approximation, apart from the fact that observations of the interstellar gas have shown it to be wrong, is that the maximum observed brightness temperature in the LAB survey is $\sim 150\text{ K}$ which is greater than our best fit global T_S . This is solved by clipping the observations when generating the gas annuli, which is not an optimal solution. A different possibility is to use the assumption

$$T_S = \max(T_{S,\min}, T_{\max} + \Delta T_S). \quad (2)$$

Here, T_{\max} is the maximum observed brightness temperature for each line of sight. This ensures T_S is always greater than T . Scanning the values of $T_{S,\min}$ and ΔT_S with a step size of 10 K and 5 K, respectively, gives us a maximum likelihood for $T_{S,\min} = 110\text{ K}$ and $\Delta T_S = 10\text{ K}$. While this assumption still does not account for the complexity of the interstellar medium, the log likelihood ratio between the best fit linear relation model and the best fit constant T_S model is of the order of 1000, a significant change.

The most accurate T_S estimates come from observations of H I in absorption against bright radio sources. We gathered over 500 lines of sight with observed T_S from the literature (Dickey et al. 2009; Heiles and Troland 2003; Strasser and Taylor 2004). This covers about 0.2% of the pixels in the LAB survey, allowing for accurate column density estimates only in those pixels. After taking our best fit linear relation model and correcting the pixels with known T_S the fit was redone for the whole sky. Note that we did not change the values of $T_{S,\min}$ and ΔT_S . The log likelihood ratio of -105 tells us that this model is worse than the best fit linear relation. This is not unexpected, since the gamma rays are generated from CR interactions with the gas and if the gas distribution is wrong, we won't get the correct CR distribution from the fit. To limit the uncertainty involved with the linear relation assumption, we did another fit, limiting ourselves to the region $-10^\circ < |b| < 10^\circ$, $15^\circ < l < 165^\circ$ that covers the observations made in the Canadian Galactic plane survey (CGPS) where the density of T_S observations is the highest and is large enough to get a good fit to the LAT data. The fit in this region results in a log likelihood ratio of 28 indicating a statistically significant improvement in the fit. This is despite the observed T_S lines of sight only covering 25% of the fitted region and the values of $T_{S,\min}$ and ΔT_S not being adjusted after correcting for known T_S values.

IV. DISCUSSION

Our small exercise here has shown that for accurate DGE modeling we need to know more about the distribution of gas in the Galaxy, especially the H I distribution. The standard constant T_S assumption is not sufficient for current instruments and small adjustments cause large differences in the quality of the

resulting model. We also show that direct observations of T_S help in creating a better model of the DGE. Unfortunately, direct observations of T_S are difficult since they require high resolution telescopes and bright radio continuum sources. Some assumptions will therefore have to be made for the regions in between bright radio sources.

It must be stated here that all of the above results are model dependent. The Fermi-LAT data can only

provide us with the intensity of gamma-rays from a particular direction of the sky. Uncertainties in our modeling of contribution other than those directly related to the H I distribution will affect the value obtained for T_S . We are currently studying the systematic effects this will have on our results. We also note that even for the best fit models, the residuals show signs of structure, strongly indicating our models are less than perfect.

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