H I spin temperature with Fermi-LAT

Guðlaugur Jóhannesson[1], Seth Digel[2], Igor Moskalenko[1],
on behalf of the Fermi Large Area Telescope Collaboration
[1]Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305
[2]Stanford Linear Accelerator Center, 2575 Sand Hill Road, Menlo Park, CA 94025

Summary: We use Galactic diffuse modeling and the Fermi-LAT data to get an estimate of the global H I spin temperature. We obtain a relation between the spin temperature and maximum observed H I temperature that significantly improves the fit to the Fermi-LAT data compared to standard assumptions.

Abstract

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 spin flip 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 in the Galactic diffuse emission using the Fermi-LAT data and Galactic diffuse emission modeling along with direct observation of the spin temperature using H I absorption.

Galactic diffuse model

Given the distribution of cosmic ray sources and the injection spectra of accelerated particles, along with the distribution of gas and the radiation field in the Galaxy, the GALPROP code [1] is able to calculate the diffuse emission in every direction of the sky. 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 [2] while distribution of H_2 is found using the CO (J=1→0) survey of [3] assuming $H_2 = X_{CO}(R)\, W_{CO}$.

Methodology

To compare different assumptions for the spin temperature, we fit the diffuse emission model to the Fermi-LAT data. To account for uncertainties in the X_{CO} factor and the distribution of CR sources, we let the radial distribution of both to be free during the fit. This is accomplished by using the Galacto-centric annuli output from GALPROP as templates in a maximum likelihood fit. Each annuli is multiplied with a normalization factor for the CR flux and the CO annuli are additionally multiplied with a X_{CO} correction. We assume that the radial distribution of both CR nuclei and electrons are the same, but allow one global normalization factor for the electron to proton ratio. We have opted to keep the spectral shape of CRs fixed so that they agree with the shape of the locally observed spectra after propagation.

The whole sky fits are performed using the GaRDiAn package after preparing the Fermi-LAT data with the science tools. We use the dataset that was prepared for the EGB analysis presented by M. Ackermann (Wed. 9:00). In addition to the Galactic diffuse model, we also include all sources from the 1 year Fermi-LAT source list and an isotropic component to account for EGB emission and particle contamination. This fit is performed for different assumption of the input T_S and a likelihood ratio test is used to compare the quality of the fits.

Caveats

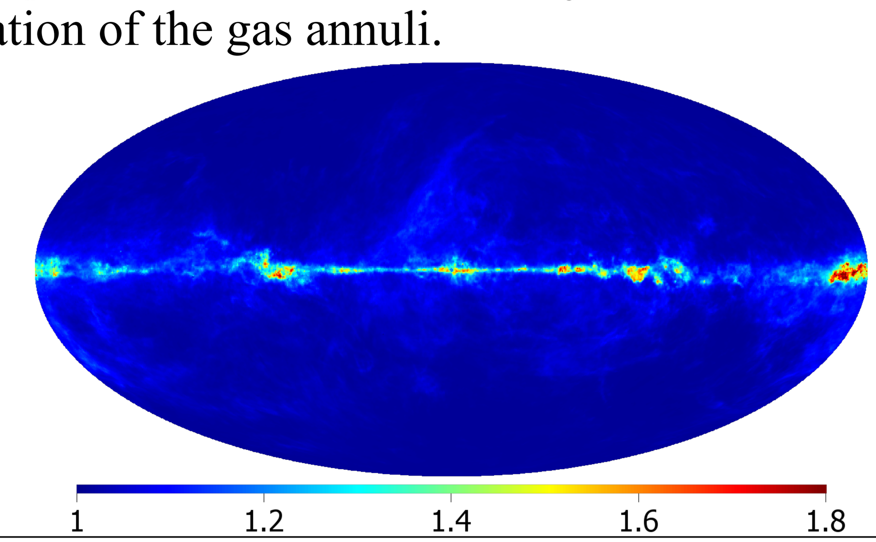
- The results presented are model dependent and we are currently studying the systematics involved.
- The resulting T_S values are valid under the assumption that components other than H I are modeled perfectly and the residual is due to incorrect T_S assumption.
- The residual of the best fit model is not flat.

H I opacity correction

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

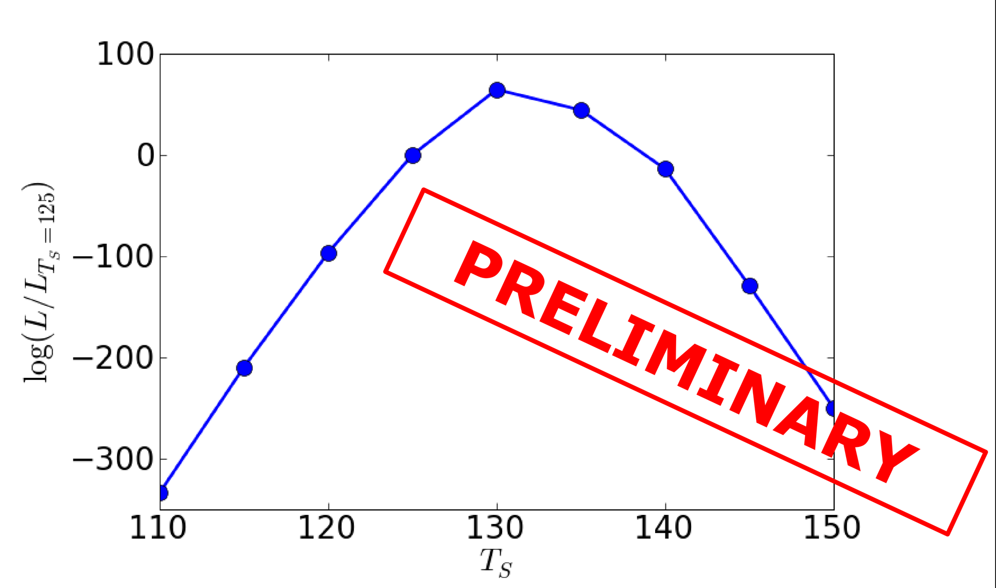
$$N_{HI}(v, T_S) = -\log\left(1 - \frac{T}{T_S - T_{bg}}\right) * T_S * C$$

where T_{bg} is the background continuum temperature and $C = 1.83\times10^{18}$ cm^{-2} K (km/s)$^{-1}$. The figure below shows 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. Note that the value of T is changed such that $T < T_S - T_{bg}$ is fulfilled in the creation of the gas annuli.



Fixed global T_S

Even though it is an inaccurate assumption we will use the best fit global T_S model as the null hypothesis for more advanced assumptions for T_S. For this we scan T_S from 110 K to 150 K in 5 K steps. We use T_S = 125 K as the baseline model for historical reasons [4]. The figure shows that T_S = 130 K gives the best fit.



References

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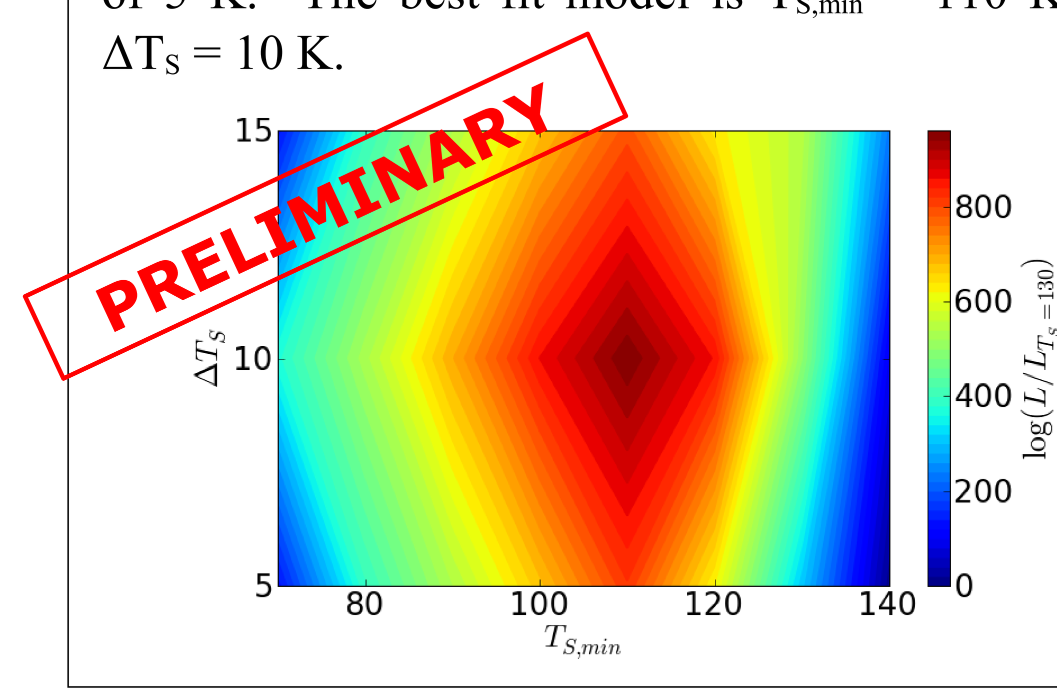
Linear relation between T_S and T_{max}

One of the problems with the fixed global T_S approximation is that the maximum observed brightness temperature in the LAB survey is ~150 K which is greater than our best fit global T_S. To rectify that, we use the assumption

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

Here, T_{max} is the maximum observed brightness temperature for each line of sight. This ensures T_S is always greater than T. The following plot shows the likelihood ratio for $T_{S,min}$ from 70 K to 140 K in steps of 10 K and ΔT_S from 5 K to 15 K in steps of 5 K. The best fit model is $T_{S,min}$ = 110 K and ΔT_S = 10 K.



Observed spin temperature

The most accurate spin temperature 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 [5,6,7]. 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 relevant pixels we redid the fit for the whole sky. The log likelihood ratio of -105 indicates that this model is worse than the best fit linear relation. That is to be expected, since the results are model dependent. To limit the uncertainty involved with the linear relation assumption, we did another fit, limiting ourselves to the region -10 < |b| < 10, 15 < l < 165 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 that is significantly better than the simple linear relation model. This is despite the observed T_S lines of sight only covering 25% of the fitted region.