Toward 3D mapping of the interstellar medium in the Milky Way: impact on cosmic rays and diffuse emission

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Abstract: Over 100 years after the discovery of cosmic rays (CRs), characterizing their origin and propagation through interstellar space remains a leading problem in astrophysics. Diffuse emissions from radio to high-energy gamma rays (> 100 MeV), arising from various interactions between CRs and the ISM, ISRF and magnetic field, are currently the best way to characterize the physics of CRs throughout the Milky Way as well as galaxies other than our own. The Milky Way is the best studied normal star-forming galaxy and we will discuss our work modeling these diffuse emissions using three-dimensional (3D) models for the ISM and CR sources. We will show that incorporating 3D structure in the CR propagation code is an essential ingredient for successful modeling of the diffuse emissions.

Keywords: Milky Way, propagation, cosmic rays, diffuse gamma rays, synchrotron, gas distribution, spiral structure, 3D model

1 Introduction

Cosmic rays (CRs) fill up the entire volume of galaxies, are important sources of heating and ionization of the ISM, and may play a significant role in the regulation of star formation during the formation and evolution of galaxies. Their importance in shaping the dynamics and other physical processes in the interstellar medium (ISM) is evidenced by the fact that the energy density in CRs is comparable to that of the interstellar radiation field (ISRF) and magnetic field, as well as that of the turbulent motions of the interstellar gas. Sources of Galactic CRs include supernova remnants (SNRs), pulsars, stellar flares, all of which connect back to massive stars. It is therefore reasonable to assume that the distribution of CR sources closely follows that of star formation in Galaxies.

It is now considered a well known fact that the Milky Way is a barred spiral galaxy. The bar in the center of the Galaxy is found to extend up to a radius of 2–4 kpc and be oriented around 10–50 degrees from the line-of-sight to the Galactic center. The number of major spiral arms is usually found to be 4, although recent work indicates that 2 spiral arms that are more tightly wound around the Galactic center also fit the data. Observations then indicate that there are smaller arms or spurs in-between the major arms. The uncertainty in the structure of the Milky Way is of course due to our location within the Galactic disk. This causes difficulties in determining the 3D structure of the Galaxy. The proximity instead allows for more detailed observations, making the Milky Way the best studied normal star-forming galaxy and the only Galaxy for which we have direct observations of CR spectra.

Another major 3D structure of the Milky-Way is the warping and flaring of the disk in the outer Galaxy. The disk lies roughly in the Galactic plane in the inner Galaxy, but in the outer Galaxy the disk can deviate up to 4 kpc from the mid-plane. The Warp is also asymmetric, extending further up in the north than down in the south. The width of the Galactic disk also increases in the outer Galaxy, from around 100 pc in the inner Galaxy to over 1 kpc in the outer Galaxy. The warping and flaring are most obvious in the interstellar gas, but other components, such as stars and dust have also been observed to follow similar trends.

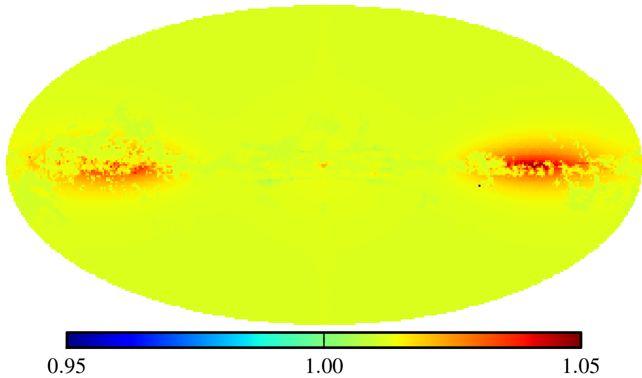

Figure 1: Ratio of pion-decay skymaps comparing 3D and 2D (3D/2D) GALPROP runs with the same azimuthally symmetric model of the Galaxy, see text for details. The maps are evaluated at 1 GeV. The maps are in Mollweide projection, with the Galactic center in the middle and longitude increasing to the left.

Despite all this knowledge of the structure of our Milky Way, CR propagation models usually assume a very simplified picture of the Galaxy. Often the Galaxy is just a thin uniform disk, although more sophisticated codes use a two-dimensional azimuthally symmetric models for the ISM and CR source distributions. In these proceedings we will show how incorporating spiral arm structure and warp in CR propagation affects the results.

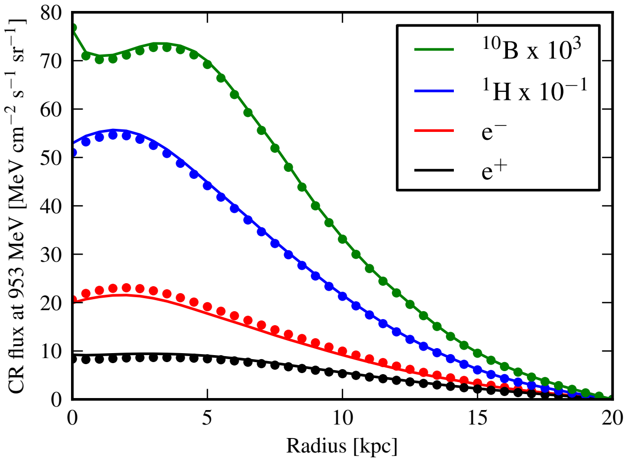

Figure 2: Radial profile for a few species comparing 2D and 3D GALPROP runs with azimuthally symmetric models, see text for detail. The dots show the 2D run while the solid lines are 3D results.

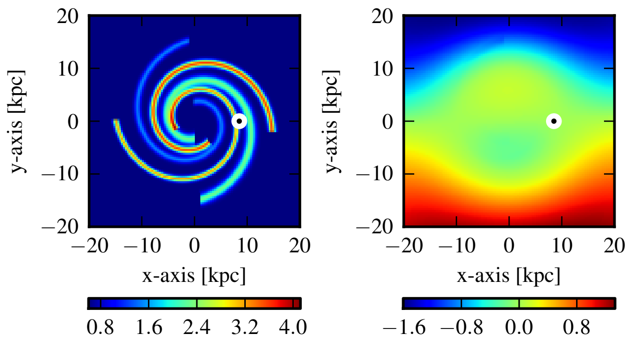

Figure 3: The surface density (left) and mean hight (right) of the model used to modulate the H I gas distribution. The arm structure and warp are clearly visible in the maps. The location of the sun is marked with a black dot in a white circle. The *x*-axis is parallel to Galactic longitude of 180° while the *y*-axis is parallel to 270°.

2 Illustrative models

We use the 4 major spiral arms from NE2001 [1] to illustrate the effects of complex 3D structures on CR propagation and the resulting CR induced diffuse emission. We limit ourselves to adding spiral arm structure in the interstellar gas and the CR source distribution but keep the 2D azimuthally symmetric ISRF. We also use the isotropic and homogeneous diffusion approximation for the propagation of CRs. The models are calculated using the GALPROP[1] propagation code. The code can be run in either 2D with a cylindrical grid (R, z) or 3D in a Cartesian grid (x, y, z). In addition to the obvious implied azimuthal symmetry in 2D, there is also a difference in the CR confinement volume. In 2D mode it is shaped as a cylinder while it is a box in 3D. This can affect the results in a non-negligible way.

Our base model is the maximum a posteriori model from [2]. This is a basic 2D diffusion model with re-acceleration that was fit to observations of nuclei CR data. The 2D gas distribution and ISRF used in the model are described in [3]. In this model the CR source distribution has a pulsar-like radial distribution that is cut off at 15 kpc. This makes the results between the 2D and 3D run more compatible because there is no addition of CR sources in the larger CR confinement volume for the 3D run. The main differences between the different GALPROP modes is illustrated in the skymap ratio shown in figure 1. The increase in CR volume shows up as increased intensity in the directions of the "corners" of the volume. The larger CR volume and the fixed energy density of the CMB causes the electrons to suffer larger energy losses in the 3D run. This is illustrated in figure 2 that shows how the electrons in the 3D run are lower over the entire radial range while the CR nuclei are not affected as much. The nuclei show a clear difference close to $R = 0$, caused by the artificial boundary of the 2D run. Otherwise the results for nuclei are nearly identical between the two runs.

In addition to the NE2001 spiral arm structure, we also apply warping to the outer Galaxy, similar to the one in [4]. The spiral arm structure and warping is applied in such a way to keep the azimuthal average of the distribution identical to the base model. This better illustrates how the 3D structure can have a large effect on the results without modifying the global properties of the Galaxy. Figure 3 shows the surface density and the mean hight of the 3D model we use to modulate our distributions. The arm to inter-arm density ratio for the H_2 gas distribution and the CR source distribution is around 10 while for the H I gas distribution it is around 4. The density and scale height of the arms is not identical so the exact ratio depends on which arm we are referring to.

To separate the effects of changing the structure of the interstellar gas and CR sources we have created 3 models in addition to the azimuthally symmetric base runs. In the first model we only modify the interstellar gas components, in the second we only modify the CR sources, and in the third we modify both. We will hereafter call these models the gas model, the CR model and the CR and gas model, respectively. The predicted spectra of primary nuclei elements are hardly affected by the modifications. The same can not be said about electrons and secondary nuclei as illustrated in figure 4. The electron spectrum shows significant variation at high energy when CR sources are distributed in spiral arms. The positron fraction also shows a variation at high energy but the effect is smaller. In this case the gas distribution has an effect of about the same magnitude as the CR source distribution but the energy dependence is nearly opposite so the model with both CRs and gas only has an increase of about 10 percent over the base model. The exact magnitude of this effect depends on the exact location of the 3D structure as illustrated in figure 5. Depending on the location in the plane, the effect can be as much as 50 percent so getting the gas density at the location of the sun is very important for accurate determination of secondary CR particles. Note that even in that case, this effect is too small to explain the rising positron fraction observed by PAMELA [5], AMS [6], and Fermi-LAT [7]. The effect on secondary nuclei production is found to be mostly energy independent. The effects of the CR source distribution is in this case smaller then that of the gas distribution except at the lowest energies. The effect is in our case less than 10 percent.

The minor effects on the predicted flux of CRs at the solar location were to be expected because we did not change

1. `http://galprop.stanford.edu`

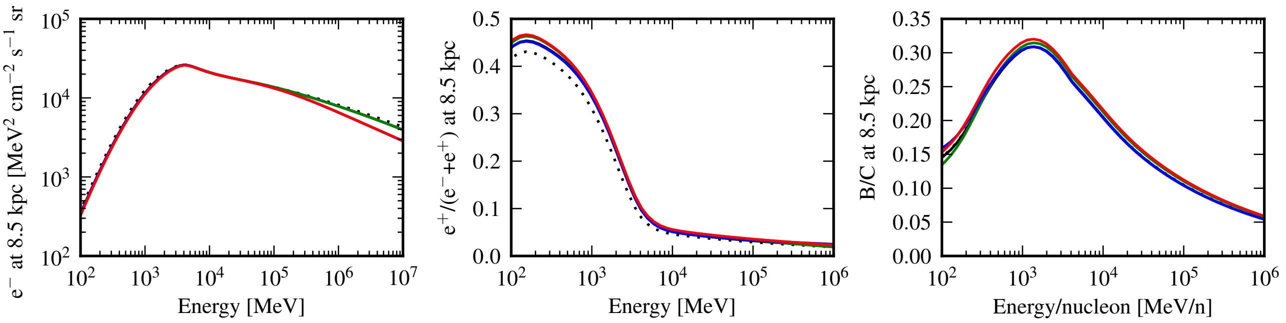

Figure 4: Interstellar spectra at the solar location of primary electrons (left, times E^3), the positron fraction (center), and B/C (right). The 3D base model is shown as black curves, gas model as green, CR model as blue and CR and gas model as red. Results from the 2D base model is shown as a black dotted curve for reference.

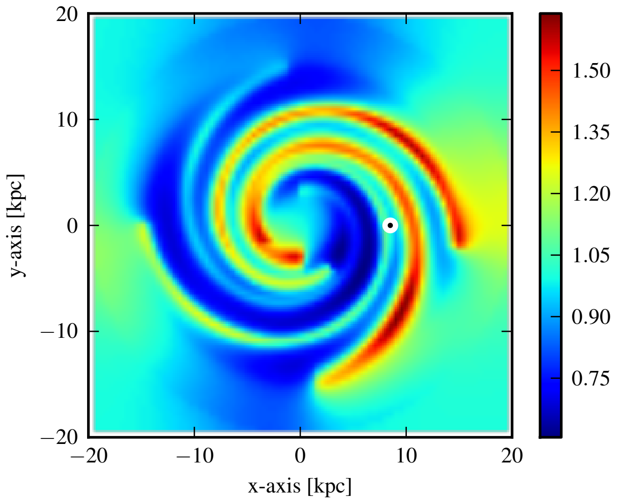

Figure 5: Predicted ratio of the positron fraction in the plane for the gas model divided by the base model at 100 GeV. The location of the sun is marked with a black dot on a white background.

the injection spectrum of CRs, or their propagation. And even though we changed the gas distribution, we did not change the total amount of gas in the Galaxy. The same can not be said about the normalization of the CR source distribution. In a standard GALPROP run the CR source distribution does not have an absolute value, but is rather normalized afterwards using the CR flux at the solar location. This is very convenient when matching CR observations, but has some interesting effects when considering distributions that are not azimuthally symmetric. Even though we keep the azimuthally symmetric distribution identical in the base model and the CR model, the normalization of the CR source distribution will depend on the exact nature of the azimuthal distribution at the solar radius. If the Sun happens to be in a low or high density region, we scale the normalization of the CR source distribution up or down, respectively, compared to the azimuthally symmetric distribution. This can have a large effect on the diffuse emissions predicted by the model because they are integrated quantities along each line-of-sight in the Galaxy. In our case the density should be increased slightly because we are in an inter-arm region, although the effect is diminished somewhat because the propagated CR distribution is a smoothed version of the CR source distribution.

The effect on the calculated diffuse emissions is illustrated in figure 6 that shows skymap ratios between the base model and the 3 modified models. The basic effects of adding the 3D structure is very similar in all the plots. We can clearly see the spiral arm structure. The large increase (red spots) just west of the Galactic center and east of the large decrease (blue spot) correspond to the start of the 2 brighter spiral arm structures, while the decrease is the start of one of the fainter spiral arms. The warp is not nearly as prominent and is not clearly visible in the figures. It should manifest as an increase in the north-east and south-west of the figure compared to north-west and south-east. The general structure of the ratio map is nearly independent of energy but the magnitude of the ratio is energy dependent. This is shown in figure 7 were we have plotted the 95 percent width of the ratio map pixel distribution. It is a good estimator for the magnitude of the effect. It clearly shows the weaker effect of the gas distribution on the diffuse emissions. The effect of the gas distribution is generally inverse to that of the CR source distribution, because the increased gas density increases the cooling rate of the particles. The only time this is not true is for low energy electrons, where the increased fraction of secondary particles makes up for the increased cooling.

3 Discussion

All of the effects discussed here are model dependent and should be considered for illustrative purposes only. This toy model does not represent the true underlying 3D structure of the CR source distribution and the gas. We also ignore the effects of the ISRF that for sure has complex 3D structure. The diffusion coefficient can also be expected to vary over the Galactic volume. The results show, however, that the effect of 3D structure is not just a secondary effect and should be taken into account when calculating CR propagation and the resulting diffuse emissions.

Acknowledgment: GALPROP development is supported through NASA Grants No. NNX09AC15G, NNX10AE78G, and NNX13AC47G

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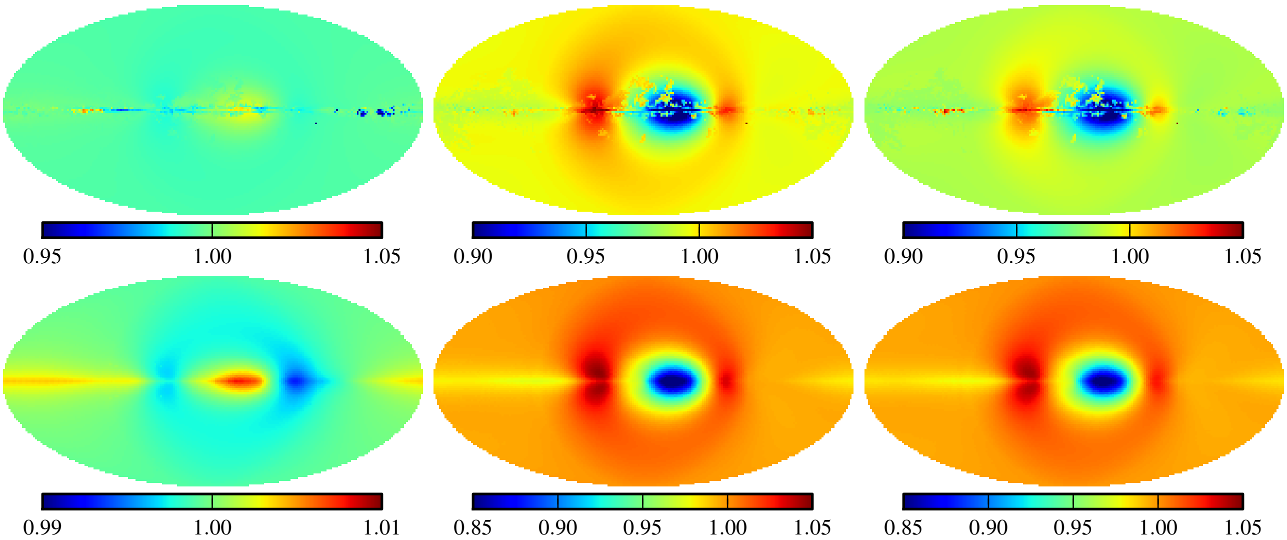

Figure 6: Ratio of pion decay skymaps (top), and synchrotron skymaps (bottom) calculated with the modified models divided with that of the base model. The pion decay maps are evaluated at energy of 1 GeV and the synchrotron map at 1 GHz. Gas model on the left, CR model in the center, and CR and gas model on the right. Note the different range for the color scale in the figures. The maps use the Mollweide projection in Galactic coordinates with the Galactic center in the middle and longitude increasing to the left.

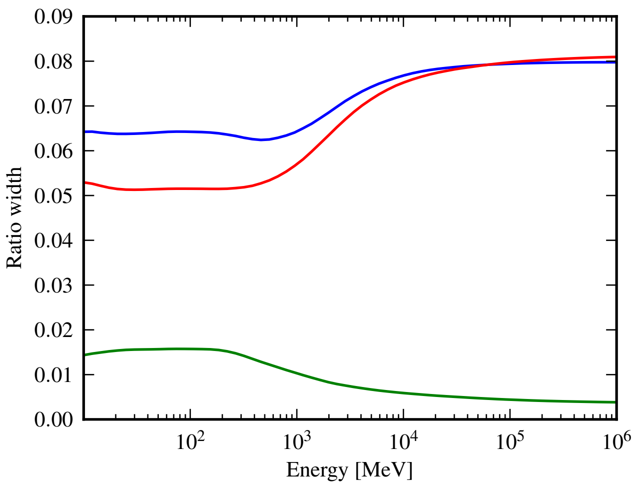

Figure 7: The width of the distribution of values from the ratio map for pion decay shown in figure 6. The width is evaluated for each energy bin such that it contains 95% of the values and is centered on the median. Shown are the curves for the gas model (green), CR model (blue), and CR and gas model (red).

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