A future very-high-energy view of our Galaxy

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Abstract. The survey of the inner Galaxy with H.E.S.S. [1, 2] was remarkably successful in detecting a wide range of new very-high-energy gamma-ray sources. New TeV gamma-ray emitting source classes were established, although several of the sources remain unidentified, and progress has been made in understanding particle acceleration in astrophysical sources. In this work, we constructed a model of a population of such very-high-energy gamma-ray emitters and normalised the flux and size distribution of this population model to the H.E.S.S.-discovered sources. Extrapolating that population of objects to lower flux levels we investigate what a future array of imaging atmospheric telescopes (IACTs) such as AGIS or CTA might detect in a survey of the Inner Galaxy with an order of magnitude improvement in sensitivity. The sheer number of sources detected together with the improved resolving power will likely result in a huge improvement in our understanding of the populations of galactic gamma-ray sources. A deep survey of the inner Milky Way would also support studies of the interstellar diffuse gamma-ray emission in regions of high cosmic-ray density. In the final section of this paper we investigate the science potential for the Galactic Centre region for studying energy-dependent diffusion with such a future array.

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BUILDING THE POPULATION

The first step in the simulation of a future survey of the Galactic plane is to establish a model for the source population. For this purpose, the sources detected in the H.E.S.S. survey of the inner Galaxy (±30°) were assumed to be attributable to a single population and the following observables were compared between these sources and a synthetic population:

- Number of detected sources
- Galactic longitude and latitude distributions
- Gamma-ray flux distribution
- Angular size distribution

Two different source population models have so far been tested separately: an SNR-type and a PWN-type model. In the following we will focus on the SNR population model. To match the number of sources, the frequency of SNe in our Galaxy was fixed to 10 per century. For the distribution of Galactic latitudes and longitudes of the underlying population we used a 3-dimensional distribution of sources in our Galaxy and a distribution of the radial distribution were taken from a model of SNRs in our Galaxy (see Fig. 1) as given in [3]. As mentioned before, in this model, the ad-
justable parameters (to match the H.E.S.S. distributions) are:

- SNR TeV gamma-ray lifetime
- Efficiency of transferring explosion energy into kinetic energy of protons

With these parameters a distribution of sources based on the SNR-model can be constructed and compared to the above mentioned H.E.S.S. distributions.

MATCHING THE H.E.S.S. POPULATION

The distributions of gamma-ray fluxes, galactic latitudes and angular sizes of the H.E.S.S. sources in the inner Galaxy were fitted to the respective distributions from the population. It seems clear from the fit (as already suggested in the initial publication about the H.E.S.S. survey [2]), that the scale height of the sources above the Galaxy must be rather small to match the narrow distribution of H.E.S.S. sources in Galactic latitude. Figures 2 show the distribution in Galactic latitude and in Log(N)-Log(S) for the model and the H.E.S.S. data. The H.E.S.S. Log(N)-Log(S) distribution follows a power-law with index \( \sim -1 \). A reasonable agreement between the model and the H.E.S.S. data can be achieved with the following parameters:

- Number of SN explosions/century: 10
- SNR TeV gamma-ray lifetime: \( 10^4 \) years
- Scale height of the SNR distribution: 30 pc
- Efficiency of converting explosion energy into cosmic rays: 9%
- Average density of surrounding medium: \( 0.5 \text{ cm}^{-3} \)

With this population of sources we can reproduce the distribution of sources and with this and the H.E.S.S. exposure map of the Inner Galaxy and the H.E.S.S. background we can simulate the survey of the inner Galaxy with both a H.E.S.S.-like and a future instrument.

A FUTURE VIEW OF THE INNER GALAXY

Using the population model derived in the previous section and extrapolating this population to lower fluxes, we can now make an educated guess at what a future TeV gamma-ray instrument might be able to detect in a survey of the inner Galaxy. Starting from the model population, we have to include the instrument response function, i.e., the effective area and the point-spread function of the instrument (as adjustable parameters) to predict the number of detected gamma rays for the given population model. We use the H.E.S.S. residual (photon-like) background weighted by an adjustable parameter which denotes how much better the background-rejection of a future instrument will be relative to the H.E.S.S. system. In addition to the population of sources we also add diffuse gamma-ray emission from \( \pi^0 \)-interactions using CO maps [8] and assuming solar system cosmic ray (CR) densities throughout the Galaxy.

Figure 3 shows simulated maps for the population of sources derived in the previous section, one for an instrument with H.E.S.S. effective areas, background rejection and angular resolution (top) - it should be noted that in this case instead of using the sources from the population, we used the measured parameters of the H.E.S.S. sources in the inner Galaxy (in terms of flux normalisation, spectral power-law index, position and extension) to enhance the similarity to the well-known H.E.S.S. survey picture [2]. This is why, e.g., we see a shell-type SNR at the position of RXJ1713.7-3946. Nevertheless, the distribution of these parameters for the population model matches the distribution of H.E.S.S. sources as derived in the previous section. The bottom plot of Figure 3 shows a simulated significance map for a future survey of the
inner Galaxy. Again, for the brightest sources the parameters of the H.E.S.S. sources have been used, whereas to extrapolate to lower fluxes we used the sources from the population model. For this bottom plot, the exposure is a maximum of 5 hours at any given point on the survey map was required (i.e., a more even exposure than in the original H.E.S.S. survey). For this particular map, the effective area of the future array was 10 times that of H.E.S.S. and both the angular resolution and the background rejection were conservatively improved only by a factor of 2, resulting in an overall sensitivity increase by a factor of $2 \times \sqrt{10} \times \sqrt{2} \sim 9$.

**PROBING ENERGY-DEPENDENT DIFFUSION**

In the plots shown in the previous paragraph we have integrated over the whole energy range of a future Cherenkov array. A natural extension to that scheme would be to split the energy range into several bands to see how well spectral parameters can be measured. As a first example of such an approach, we split the simulated diffuse emission from interaction of cosmic rays within interstellar gas in the Galactic Center region into several energy bands and show in Figure 4 only the highest and the lowest range ($0.1-0.3$ TeV, and $E > 3$ TeV). With this approach we can test how well a future Cherenkov instrument might study energy-dependent diffusion - assuming a central source illuminates the clouds in the GC region.

For Figure 4 CS data have been used to trace the target material distribution (note that the unknown $z$-distribution was assumed to be flat). The CR distribution was chosen as a 3-dimensional Gaussian with energy dependent width, corresponding to burst-like injection in the past (e.g. a SN explosion). The diffusion coefficient normalisation at 1 TeV was chosen to match the H.E.S.S. data in the GC region and an energy dependence of the
form $D(E) \sim E^{0.6}$ was assumed. Using a power-law injection energy spectrum of the CRs we derived the spatial distribution of CRs in the GC-region. Using this distribution of CRs we calculated the distribution of $\pi^0$-decay gamma-rays following the parametrisation of Kelner et al. [9]. The gamma-ray maps shown in Figure 4 have been smeared with the estimated (energy-dependent) angular resolution of a CTA/AGIS-like instrument and the probability density distribution for gamma-ray detection has been plotted in the two energy bands specified above. A missing step in this study (to be added in a future step) is the addition of background and the sampling of photons with Poisson statistics.

**SUMMARY**

This study provides a first glimpse of what a future array of ground-based Cherenkov telescopes such as AGIS or CTA might be able to study in the inner part of the Galaxy. We have constructed a population model based on a distribution of SNR-like sources that is able to explain the global properties of the H.E.S.S.-detected sources. Extrapolating this population to gamma-ray flux values below the H.E.S.S.-sensitivity gives a prediction of the richness of objects that we might be able to study with a future instrument. Depending on the exact parameters of the simulation we expect $\sim 300$ sources above the flux sensitivity limit of CTA/AGIS for the inner 30° of the Galaxy. Next steps will include trade-off studies between angular resolution, energy threshold and effective area to guide the choice of array parameters. Detailed studies are needed for a wide range of astrophysics topics to educate such a parameter choice. We have begun work on the specific area of the energy-dependent diffusion in the Galactic Centre region, as a step towards this.

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