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Diffuse Galactic Gamma-ray Emission with H.E.S.S.

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While imaging atmospheric Cherenkov telescopes have been very successful in the discovery and detailed measurement of γ-ray sources, observation of large-scale diffuse emission has been complicated by their small field of view. With the H.E.S.S. Galactic plane survey exists for the first time a deep-exposure data set of large spatial extension, covering the central part of the Milky Way. In the analysis of these data, a signal of large-scale γ-ray emission along the Galactic plane is detected in regions off significantly detected γ-ray sources. This is the first time that large-scale γ-ray emission is observed by imaging atmospheric Cherenkov telescopes. Due to the imperfect γ-hadron separation and the applied background subtraction, the analysis is only sensitive to signals of extensions in Galactic latitude that are small compared to the H.E.S.S. field of view. Emission with larger scale height can be recovered only partly.
Contributions to the observed signal originate probably from unresolved γ-ray sources and a truly diffuse emission of hadronic interactions with π^0 decay and inverse Compton scattering. Calculations show that the minimum γ-ray emission from π^0-decay represents already a significant fraction of the total signal. While unresolved sources provide the smallest scale height and are recoverable to a large extend, the hadronic emission via π^0 decay follows the broader gas distribution and looses around a third of its signal. The inverse Compton component depends at TeV γ-ray energies on the short lifetime and propagation distances of the emitting electrons and renders predictions difficult. At lower energies a smooth emission with large scale height results in a signal loss of $\sim 95\%$.

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1. Introduction

While γ-ray observations in the MeV/GeV range are usually performed with satellites, at higher energies ground-based facilities take over and measure the air shower that the γ-ray initiates in the atmosphere. These experiments either measure an intersection of the air shower by particle detectors using water Cherenkov detectors (like Milagro [1] and HAWC [2]) or carpets of particle detectors (like ARGO-YBJ [3]), or work calorimetricly using the atmosphere, as in the case of imaging atmospheric Cherenkov telescopes (IACTs). All in common have large effective areas necessary for the detection of very-high-energy (VHE) γ-rays with their low fluxes and steeply falling spectra. IACTs furthermore feature high sensitivity and good γ-hadron separation capability, excellent angular and good spectral resolution, but suffer from low duty cycles of around 1000 hours per year and small fields of view of a few degrees [4]. These properties make IACTs excellent instruments for the observation of γ-ray sources with limited extension. The good sensitivity makes the detection of faint sources possible, and together with the angular and energy resolution allows morphology and spectral studies of sources that show extension of a few degrees maximum. The measurement of large-scale emission, however, faces serious problems, as will be discussed later.

As VHE γ-rays are produced in interactions of cosmic rays, either hadronically by interactions with interstellar matter via π^0 production and decay or leptonically by inverse Compton scattering on radiation fields, observation of γ-ray sources reveals enhancements of cosmic rays and thereby allows to trace their accelerators. In order to study cosmic rays in the Milky Way, the key questions regard not only their acceleration but also their propagation. The propagation of cosmic rays can be traced by diffuse γ-ray emission, which originates from cosmic rays that have escaped their acceleration site and propagate freely in the Galaxy. Such emission is observed in the neighbouring energy band by Fermi-LAT [5]. Here, the diffuse emission is the dominant feature in the sky, outshining most γ-ray sources. As the cosmic rays are thought to propagate via energy-dependent diffusion, their spectrum steepens during propagation, yielding a steepened diffuse γ-ray spectrum compared to the source spectra. As a consequence, at TeV energies the sky is no longer dominated by the diffuse emission as observed at MeV energies but rather by the γ-ray sources, and the diffuse γ-ray emission is reduced to a very faint signal. Observations of diffuse γ-ray emission in the VHE regime exist by Milagro [1] at a median energy of 15 TeV, and by ARGO-YBJ [3]. While these experiments can provide the large field of view (and additionally the superior duty cycle) favouring a measurement of large-scale emission, they are limited in their γ-hadron separation possibilities and in their angular resolution, which is a key feature for the discrimination between γ-ray sources and diffuse emission signatures.

2. The H.E.S.S. Galactic Plane Survey

The system of IACTs that has been driving the field of VHE γ-ray astronomy most intensely in the past decade is the High Energy Stereoscopic System (H.E.S.S.). Situated in the Khomas Highland in Namibia with excellent viewing conditions on the Galactic Center and the central part of the Milky Way, it has been taking data since 2004 as an array of four identical telescopes, each one equipped with a mirror of 12 m in diameter (H.E.S.S. I). In 2012, the experiment was expanded

by a single 24 m telescope in the middle of the original array (H.E.S.S. II).
In its 10 years of operation, the H.E.S.S. I telescopes have scanned the central part of the Milky Way, collecting a unique deep-exposure data set of VHE γ-ray emission in the longitude range of $-75^\circ < l < 60^\circ$ and latitude range of $-2^\circ < b < 2^\circ$. The H.E.S.S. Galactic Plane Scan (HGPS) is one of the major achievements of H.E.S.S. I and has discovered a wealth of new γ-ray sources, most of them extended and with complex morphologies [6]. With its large extension and deep exposure, this data set offers the potential to study also large-scale diffuse VHE γ-ray emission with IACTs. However, a large-scale emission measurement involves some intrinsic problems for IACTs, which need to be adequately addressed in the analysis and taken into account in the understanding of the result to be obtained. The good angular resolution of IACTs presents us with a large number of γ-ray sources with irregular shapes. A modelling of such γ-ray sources, as required for a measurement of the underlying diffuse emission, is very difficult. Additionally, the imperfect γ-hadron separation requires a subtraction of the remaining background of γ-like hadronic events. This is customarily done via a background measurement in the same field of view [7], a technique which yields very reliable results for small sources but limits the size of sources to be observable. Together with the small field of view of IACTs the size of emission regions to be probed is limited to a few degrees. If a signal exhibits extensions of the size of the field of view or larger, the background subtraction procedure will eliminate the signal by subtracting it together with the hadronic background. Thus the absolute level of a signal cannot be recovered, but only gradients in the signal are observable.

3. The measurement of large-scale diffuse emission with H.E.S.S.

For a measurement of large-scale diffuse Galactic γ-ray emission, the data of the HGPS has been analysed [8]. In order to avoid the complex modelling of extended γ-ray sources needed for a global measurement of diffuse emission in the Galactic plane, γ-ray sources are excluded from the analysis and only regions of no significant detection of γ-ray emission are considered. These regions are shown in white in the top panel of Fig. 1. The crucial measurement of the hadronic background has been performed in regions beyond a Galactic latitude of $\pm 1.2^\circ$ without any significant γ-ray emission. This box of $\pm 1.2^\circ$ in latitude that is excluded from background measurements is indicated by dashed lines in the top panel of Fig. 1. The criteria for significant γ-ray emission are the same as for the choice of the analysis region (again indicated in white in the top panel of Fig. 1). The observed signal depends only weakly on the details of the significance threshold, but more pronouncedly on the extension of the box in latitude. This exclusion of a box along the Galactic equator has the effect of making the analysis sensitive to the scale height of the signal to be observed.
In the middle panel of Fig. 2 the longitudinal profile (the differential flux at 1 TeV averaged over the latitude range) of the full data set (including γ-ray sources) is shown, in the bottom panel the longitudinal profile of the diffuse signal of regions with no significant γ-ray emission. While in the profile of the full data set the spikes of the various γ-ray sources are clearly visible, the profile of the diffuse signal rather traces the location of regions to be excluded from the analysis and small excesses appear predominantly in longitude ranges with no or little exclusion of regions, especially at small latitudes. When considering the latitudinal profile, however, as is done in Fig. 2, a clear excess is observed for both, the full data set (top panel) and the diffuse signal (bottom panel). The

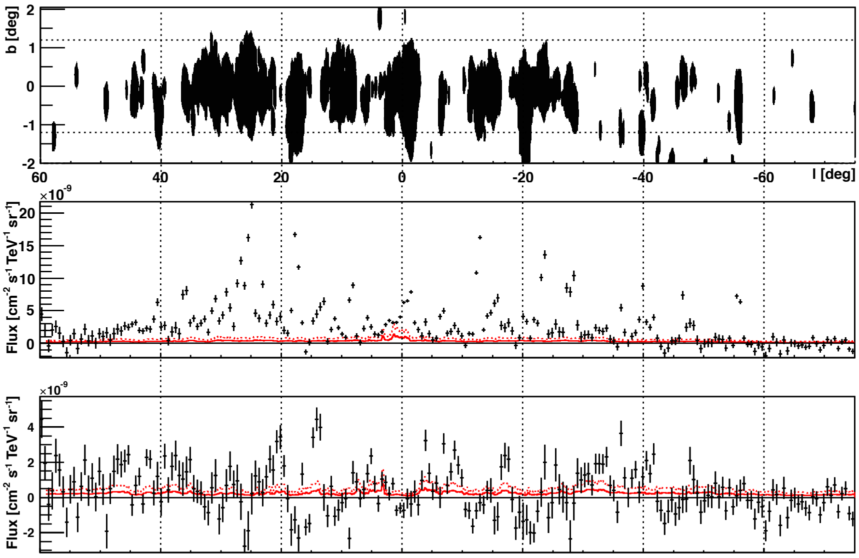

Figure 1: The regions of significant γ-ray emission (top panel) and the longitudinal profile of the Galactic plane over a latitude range of $-2^\circ < b < 2^\circ$ for the full data set (middle panel) and the regions of no significant γ-ray emission (bottom panel), reproduced from [8]. Red lines indicate the minimum hadronic model with (dashed line) and without (solid line) nuclear enhancement factor.

diffuse signal exhibits a maximum at around $b \approx -0.25^\circ$ of $3 \cdot 10^{-9}$ TeV^{-1} cm^{-2} s^{-1} sr^{-1}. The reason for this signal to be observed significantly although only regions of no significant γ-ray emission are considered, lies in the accumulation of the signal over the large range of longitude values.

4. Discussion of the origin of the signal

The observed emission can originate from interactions of propagating cosmic rays via π^0 decay or inverse Compton scattering or it can stem from unresolved γ-ray sources. These possibilities are discussed in the following.

As γ-ray sources are the dominant emission in the TeV sky, it appears very likely that also the observed diffuse signal has a large component of unresolved γ-ray sources. Due to the sensitivity limits of the HGPS, only parts of the Milky Way are significantly detected. Low-luminosity or distant sources are not resolved and their γ-ray emission contributes to the observed diffuse signal. Furthermore, such a component of unresolved γ-ray sources does not even suffer a suppression due to the effect of background subtraction: As can be seen from the signal of the total γ-ray emission including sources, the location of the γ-ray sources are neatly aligned with the Galactic equator. In addition, more distant sources are expected to be even more confined due to the projection effect. The signal has a low scale height and is thus recoverable by the discussed analysis to a large extend. A quantitative investigation of the contribution of unresolved sources will be possible with the upcoming catalog of H.E.S.S. sources in the HGPS with the use of source population synthesis. Another component that has to be present in the signal at some level is the emission caused by π^0

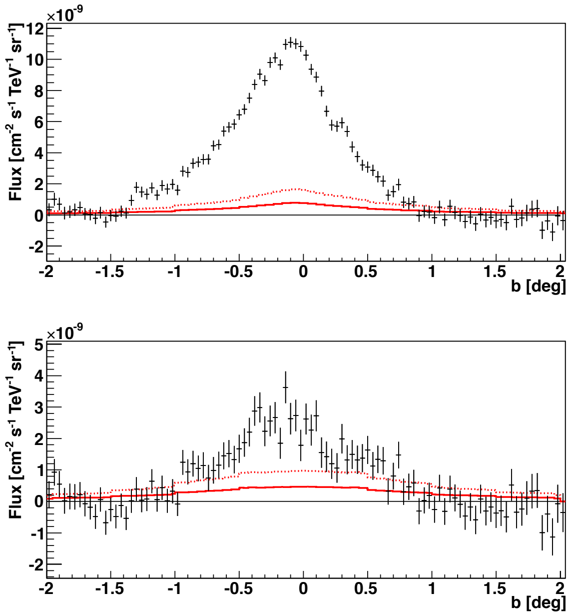

Figure 2: The latitudinal profile of the Galactic plane over a longitude range of $-75^{\circ} < l < 60^{\circ}$ for the full data set (top panel) and the regions of no significant γ-ray emission (bottom panel), reproduced from [8]. Red lines indicate the minimum hadronic model with (dashed line) and without (solid line) nuclear enhancement factor.

decay of hadronic interactions. An estimation of this contribution can be obtained by investigating the minimum emission that needs to be present due to interactions of the sea of cosmic rays present throughout the Galaxy. Assuming the sea of cosmic rays to correspond to the cosmic-ray spectrum measured at Earth [9], limiting the target material to atomic (from the Leiden-Argentine-Bonn Survey [10]) and molecular hydrogen (determined from CO measurements by Nanten with a constant conversion factor $X_{CO} = 2 \cdot 10^{20}$ cm^{-2} K^{-1} km s^{-1} [11]), and using the parametrisation by Kelner et al. [12] for the interaction cross section, the resulting emission is visualised by red curves in Figs. 1 and 2. In addition, the effect of considering heavier nuclei by the use of a nuclear enhancement factor of 2.1 [13] is visualised by the dashed lines. Due to the larger scale height of the gas distribution, only around two thirds of the signal can be recovered by the analysis, one third is lost in the process of the background subtraction. This results in a *minimum* contribution of 17% (36% when considering heavier nuclei) of the diffuse signal to originate from hadronic interactions via π^0 decay.

Leptonic cosmic rays emit γ-rays via inverse Compton scattering. At lower energies, the emission is rather smooth owing to the smooth distribution of the radiation fields and the cosmic-ray electrons at these energies. For such signals the emission exhibits such a large scale height that around 95% of the signal is lost in the process of background subtraction. At TeV γ-ray energies, however, the lifetime of the emitting electrons is drastically reduced to $\sim 10^4$ years resulting in propagation distances of ~ 100 pc. This leads to a very inhomogeneous distribution of cosmic-ray electrons, which strongly depends on the distribution of accelerators that currently release cosmic-ray electrons at several tens of TeV.

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5. Conclusion

While IACTs with their small field of view appear to be not very suited for the measurement of large-scale emission, they feature the sensitivity and angular resolution necessary to separate the γ-ray sources from the diffuse signal. H.E.S.S. has with its Galactic plane survey collected a data set that contains both, a multitude of γ-ray sources and a signal of large-scale diffuse emission. This measurement of diffuse emission is the first observation of a large-scale signal by IACTs. For a more detailed investigation of the origin of this emission, a better understanding of the population of γ-ray sources in the Galactic plane as well as the cosmic rays at several TeV energies, especially the electrons is needed.

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