The Spectral Energy Distribution of Galaxies
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The H.E.S.S. view of the Milky Way in TeV light

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Abstract. Since 2003 the H.E.S.S. collaboration has been operating an array of four imaging Cherenkov telescopes in the Khomas Highlands of Namibia. H.E.S.S. can detect gamma rays in the energy range 100 GeV to 100 TeV, has a large field of view (5 degree), good angular resolution (0.1 degree), energy resolution (15%) and sensitivity (a 1% Crab flux point source is detected at 5 sigma significance in 25 h). About half of the available observing time has been spent on the Milky Way, either in scan mode or on individual sources, resulting in the detection of more than 60 Galactic TeV sources. In this talk the two most numerous source classes will be discussed, pulsar wind nebulae and supernova remnants. For the identification and understanding of the TeV emission seen by H.E.S.S. additional measurements of non-thermal emission, mainly in the radio, X-ray and lower-energy gamma-ray bands, are critical. Since August 2008 the Fermi Large Area Telescope has been scanning the whole sky in the energy range from 20 MeV to more than 300 GeV and has detected about 200 Galactic sources as well as diffuse emission from the Milky Way. This talk will give an overview of Galactic H.E.S.S. observations in the multi-wavelength context, with a focus on Fermi.

Keywords. surveys, gamma rays: observations, cosmic rays, Galaxy: structure

1. Introduction

Most of the contributions to this conference on 'The spectral energy distribution (SED) of Galaxies' study the thermal emission by the stars and dust in the Milky Way and other Galaxies. Yet all of this emission lies in the rather narrow energy band from 0.01 to 10 eV and represents only a small part of the total SED. Figure 1 illustrates the full SED, including the nonthermal emission components which range from low-frequency radio at 10^{-8} eV to very-high-energy gamma rays at 10^{14} eV. Here we give a short introduction to the progress made in the last years by the surveys of the gamma-ray emission of the Milky Way by the H.E.S.S. (`http://www.mpi-hd.mpg.de/hfm/HESS/`) and Fermi (`http://fermi.gsfc.nasa.gov/`) telescopes.

The Milky Way contains populations of cosmic particle accelerators that produce high-energy cosmic ray electrons, positrons and nuclei, typically with power-law spectra, reaching in some cases 10^{15} eV or more. The electrons interact with ambient magnetic fields and emit synchrotron radiation from radio to X-ray energies. They also produce inverse Compton gamma-ray emission in interactions with ambient low-energy photon fields such as the cosmic microwave background or stellar, dust and synchrotron radiation. Nuclei interact with surrounding gas and produce gamma-ray emission via neutral pion decay. Figure 1 illustrates the resulting SED components. The luminosity of the emission in each case is proportional to the product of cosmic ray and target density, both of which can be a few orders of magnitude higher inside and near the cosmic accelerators compared to the average densities in the Milky Way of $B \sim 1\,\mu$G and $n \sim 1\,\mathrm{cm}^{-3}$. The lifetime of most cosmic accelerators is 10^3 to 10^6 years, yet the average time it takes a cosmic

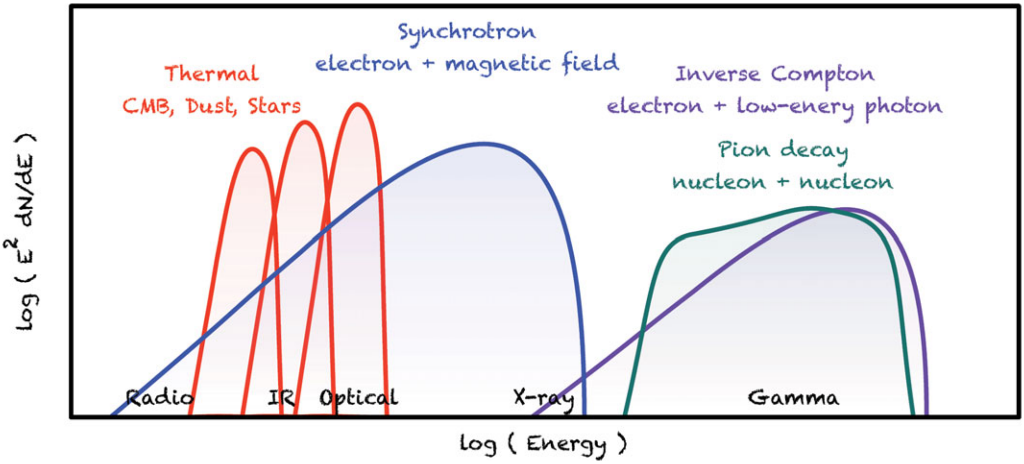

Figure 1. Illustration of the non-thermal SED components produced by cosmic rays as well as the thermal components (cosmic microwave background, emission by dust and stars) which can represent target photon fields for interaction with high-energy electrons, producing inverse Compton emission gamma rays.

ray particle to diffuse (due to gyromotion in the turbulent Galactic magnetic field) out of the Milky way is 10^7 years, so in addition to the sources there is a diffuse emission component arising from a 'sea of cosmic rays' interacting with passive targets.

The largest Galactic source class for the Fermi LAT survey at GeV energies are pulsars. For the H.E.S.S. survey at TeV energies the largest identified source classes are pulsar wind nebulae (PWNe) and supernova remnants (SNRs), sometimes interacting with nearby molecular clouds (MCs). Pulsars and PWNe are thought to be mostly electron (and positron) accelerators (Gaensler & Slane 2006), which originate from pair production in the pulsar magnetosphere (Daugherty & Harding 1982). It is possible that electrons and nuclei are 'ripped out' of the pulsar and thus PWNe have a more complicated composition than an electron-positron plasma (Horns *et al.* 2007). SNRs accelerate both electrons and nuclei from the thermal gas present in the shock wave acceleration zone. For most SNRs observed in gamma rays it is unclear which emission mechanism—leptonic or hadronic—dominates, the observed SEDs can be explained using either or a mixed model. For example for RX J1713.7-3946 a leptonic model is favoured (Abdo and Fermi LAT Collaboration 2011), for Tycho's SNR a hadronic model (Morlino & Caprioli 2011).

2. H.E.S.S. Galactic plane survey

H.E.S.S. is an array of imaging atmospheric Cherenkov telescopes that performs pointed observations with a field of view of ~ 5 deg. It detects extended air showers in the Earth's atmosphere induced by gamma rays and a background of cosmic rays and reconstructs the energy and direction of each event. Since the start of its operations in 2003 it has spent about half of the available observing time (~ 1000 h/yr) on the Galactic plane survey (GPS) region $l = -100$ to $+60$ deg and $b = -3.5$ to $+3.5$ deg, resulting in ~ 2300 h of good-quality observations. The GPS observations are again split 50/50 on systematic scan-mode observations and observations on specific targets that have been identified at other wavelengths or discovered as 'hotspots' in the scan-mode observations—see Gast *et al.* (2011) for the latest update. The resulting sensitivity (expressed in units of the

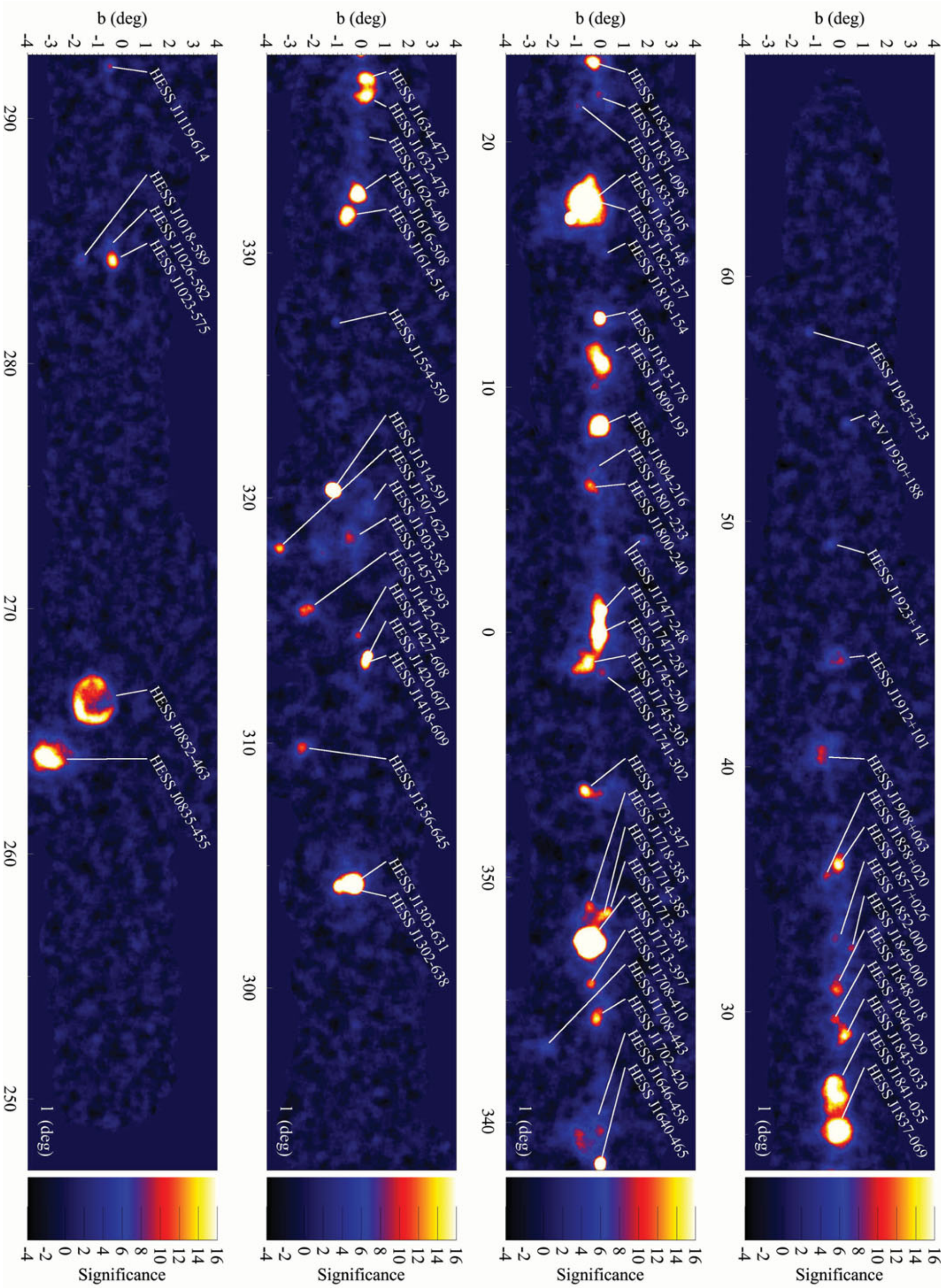

Figure 2. Latest significance map for the H.E.S.S. Galactic plane survey. This image shows for each position the statistical significance of the observed excess over the background within a correlation radius of 0.22 deg. The color transition to red occurs at approx. 7 sigma, which is typically chosen as the requirement for detection. Figure reproduced from Gast *et al.* (2011).

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Crab integral flux $F(>1\text{TeV}) = 2.26 \cdot 10^{-11}$ cm^{-2} s^{-1}) for point sources in the Galactic plane varies from 0.5% Crab to 3% Crab. Because most pointings are located within $b = \pm 1$ deg and the H.E.S.S. sensitivity deteriorates at the edges of the FOV, the sensitivity increases by a factor of 3 at $b \sim \pm 3$ deg. Latitudes $b = \pm 4$ deg are practically not surveyed except for a few small longitude regions. The H.E.S.S. sensitivity is limited by background from cosmic-ray-induced air showers. Over 99% of the events the array initially triggered on and recorded shower images can be discarded as cosmic-ray background during offline analysis (Ohm *et al.* 2009). Still for the gamma-hadron separation cuts used to produce Figure 2, only 2.2k ($\sim$ 6%) of the 3.6M events used to compute that significance map are actually photons. The remaining background is modelled as described in Berge *et al.* (2007). For the background methods usually used to make images (field of view and ring method) and spectra (reflected region method) of gamma-ray sources, possible diffuse gamma-ray emission on the scale of the FOV (5 deg diameter) or even smaller (ring diameter of 0.5 to 4 deg) is included in the background model and thus effectively subtracted in flux and significance map production.

More than 60 sources have been discovered. They range in size from spatially unresolved faint (0.5% Crab) sources like the recent discovery of W49B ((Brun *et al.* 2011, Brun *et al.* 2011), not yet labeled in Figure 2) to the SNR Vela Jnr (HESS J0852-463, (Aharonian *et al.* 2007, Aharonian *et al.* 2007)) with a diameter of 2 deg and a flux of $\sim$ 70% Crab. Other prominent sources are the SNR RX J1713.7-3946 and two very extended and bright PWNe, HESS J1825-137 and HESS J1303-631, for which an energy-dependent morphology could be established, with the higher-energy ($\sim$ 10 TeV) emission concentrated in a small area around the pulsar and the lower-energy ($\sim$ 1 TeV) emission extending much further out. The physical explanation is that the acceleration process and thus the injection of electrons occurs close to the pulsar and then the particles cool via adiabatic or radiation losses as they move away. About one third of the Galactic H.E.S.S. sources are unidentified. In some cases no good multiwavelength counterpart is known, and sometimes several viable counterparts exist. For example the point source HESS J1745-290 coincides with the position of the supermassive black hole Sgr A* (offset $8 \pm 9_{stat} \pm 9_{sys}$ arcsec) in the centre of the Milky Way (Acero *et al.* 2010), but could also be explained as emission from the PWN candidate G359.95-0.04. The H.E.S.S. source catalog at `http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/sources/` and TeVCat `http://tevcat.uchicago.edu/` are excellent sources of information and contain further references for each source. The H.E.S.S. survey data is currently not publicly available, although there is a plan to publish GPS maps in FITS format and a corresponding source catalog in the future.

3. Multiwavelength context: The Fermi LAT survey

For the identification and characterization of the physical properties of Galactic H.E.S.S. sources it is crucial to combine the H.E.S.S. measurement in the rather narrow energy range (typically 0.3 to 30 TeV) with observations at lower energies. For example it is possible to infer or derive limits on the magnetic field strength in cosmic electron sources from the ratio of observed X-ray synchrotron flux and TeV gamma-ray inverse Compton flux. At optical and infrared wavelengths the thermal starlight and dust emission typically dominates by several orders of magnitude over the nonthermal emission, which is the reason why radio and X-ray observations are often used to search for counterparts and to understand the physical conditions in TeV sources.

In 2008 the Fermi LAT pair production telescope started to perform an all-sky survey, the data is publicly available. Figure 3 shows the count maps obtained in four decades of

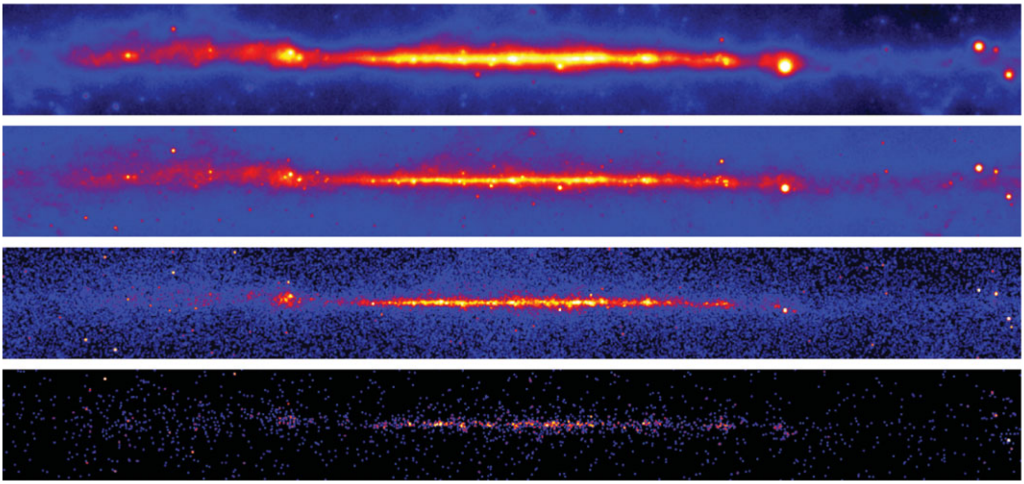

Figure 3. Fermi LAT count maps of the Galactic plane (CAR projection, GLON = -180 to +180 deg, GLAT = -10 to 10 deg, 0.1 deg binning, smoothed with 0.5 deg Gaussian for better visibility of the single events in the high-energy band). Top to bottom 0.1 to 1 GeV (20M events), 1 to 10 GeV (3.5M events), 10 to 100 GeV (90k events), 100 to 1000 GeV (3.5k events). 31 months exposure, P6_V3_DATACLEAN cuts.

energy (0.1 – 1– 10 – 100 – 1000 GeV) using 31 months of data. The diffuse emission from the Milky Way as well as individual sources are clearly visible. At low energies the Fermi measurements in the Galactic plane are limited by the low angular resolution ($\sim$ 10 deg at 100 MeV, improving by almost 2 orders of magnitude at the highest energies), due to a high level of diffuse background emission and high source density. At high energies the sensitivity is limited by the accumulated exposure, above 100 GeV a cluster of only a handful of photons represents a highly significant source. The average exposure at high energies for 31 months of data in the inner Galaxy is $\sim 8 \cdot 10^{10}$ cm^2 s. Even for one of the brightest sources in the sky, the Crab nebula, only $\sim$ 50 photons will be detected above 100 GeV given its integral flux of $F(> 100\mathrm{GeV}) \sim 6 \cdot 10^{-10}$ cm^{-2} s^{-1}(Meyer *et al.* 2010).

The Fermi collaboration has published the 2FGL catalog (The Fermi-LAT Collaboration 2011), where they have modelled the total emission as the sum of the isotropic and Galactic diffuse background components plus 1861 point and 12 extended sources. This works extremely well for the extragalactic sky. For the Galactic plane they find $\sim$200 sources, although one has to note that given the high source density and the fact that many sources are actually extended, there are cases where big and bright sources are represented as multiple entries in the catalog (e.g. three 2FGL sources for Vela Jnr). The latitude distribution is very narrow, even though Fermi has a better sensitivity for sources at higher latitudes, because the Galactic diffuse emission there is weaker. It seems that even though the H.E.S.S. GPS region only covers 3% of the sky, most Galactic sources above the H.E.S.S. sensitivity limit have already been found.

4. Outlook

Currently the H.E.S.S. collaboration is constructing a fifth, much larger H.E.S.S. II telescope (600 m^2 reflector) in the centre of the array of the four H.E.S.S. I telescopes (100 m^2 reflector each). H.E.S.S. II will allow measurements in the gap in the measured SEDs around 100 GeV that is currently present for most gamma-ray sources seen by Fermi

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and H.E.S.S. as well as provide better sensitivity over the full energy range (Becherini *et al.* 2010). It is worth noting that due to its smaller FOV compared to H.E.S.S. I (3.5 instead of 5 deg), a survey of large parts of the Milky Way is not possible. Instead H.E.S.S. II (and H.E.S.S. I - the full array will most likely not be split up to observe different targets at the same time) will focus on exciting astrophysical questions of individual sources. For example we hope that with H.E.S.S. II we will be able to observe emission from gamma-ray bursts and the pulsed emission component from pulsars. Somewhat further in the future, the Cherenkov Telescope Array (CTA, `http://www.cta-observatory.org/`) will give an order of magnitude more sensitive (milli-Crab), higher-resolution view of the Galaxy in the energy range 10 GeV to 100 TeV. It will be operated as an observatory where everyone can apply for observation time and after some time all data becomes publicly available. The High-Altitude Water Cherenkov Gamma-Ray Observatory (HAWC, `http://hawc.umd.edu/`) is currently being constructed in Mexico and will survey the whole southern hemisphere in the energy range 100 GeV to 1000 TeV. CTA and HAWC will be complementary instruments. HAWC has a large field of view and high duty cycle, whereas CTA has a low energy threshold, high sensitivity and good angular resolution. At least for the next five years, though, the H.E.S.S. Galactic plane survey in combination with the Fermi all-sky and other lower-energy surveys will be the best dataset to study the populations of Galactic cosmic accelerators.

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Discussion

Romero: You mention that the γ-ray emission from RX J1713-39 is likely to be leptonic. This is in contradiction with one of the claims of the previous speakers. Can you justify your claim please?

Deil: The claim that the emission is likely to be leptonic was made by the Fermi Collaboration based on their measured spectrum (combined with the HESS spectrum). I'm not sure which previous speaker or leptonic model you are referring to.

Porter: I'd like to comment on the question whether pair creation is important in SNRs: The turnover at an energy of a few tens of TeV in leptonic spectra are due to Inverse Compton in the Klein-Nishina regime on the infrared component of the interstellar radiation field. Pair creation is not important below 50 TeV on the galactic interstellar radiation field.

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