Hard spectrum of cosmic rays in the Disks of Milky Way and Large Magellanic Cloud.

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ABSTRACT

Context. The slope of the locally measured spectrum of cosmic rays varies from 2.8 for protons with energies below 200 GeV down to 2.5 for heavy nuclei with energies in the TeV-PeV range. It is not clear if the locally measured slope values are representative for those of the overall population of Galactic cosmic rays and if the slope of the cosmic ray spectrum varies across the Galaxy, e.g. in response to the variations of the star formation rate.

Aims. We use the data of Fermi Space $\gamma$-ray Telescope to derive a measurement of the slope of the cosmic ray spectrum across the Galactic Disk and to compare it with that of the Large Magellanic Cloud cosmic rays.

Methods. A special choice of the background estimation regions allows us to single out the neutral pion decay component of the $\gamma$-ray flux in the energy range above 10 GeV and to separate it from (a) emission from the local interstellar medium around the Solar system and (b) from the inverse Compton emission produced by cosmic ray electrons.

Results. The spectrum of the pion decay $\gamma$-ray emission from the Galactic disk in the energy band 10 GeV – 1 TeV has the slope $\simeq 2.4$. There is no evidence for the variation of the slope with Galactic longitude / distance from the Galactic Centre. The slope of the spectrum of cosmic rays derived from the $\gamma$-ray data, $\simeq 2.45$, is harder than the slope of the locally observed cosmic ray proton spectrum. Pion decay emission from a powerlaw distribution of cosmic rays with the same hard slope also provides a fit to the $\gamma$-ray spectrum of the Large Magellanic Cloud.

Conclusions. Identical and hard slopes of the spectra of cosmic rays in the Milky Way and in the Large Magellanic Cloud are consistent with a straightforward theoretical model in which cosmic rays are injected by shock acceleration with the spectrum of the form $\Gamma = \Gamma_0 + \frac{1}{\delta}$, which is subsequently modified by the energy dependent escape of cosmic rays through the turbulent Galactic magnetic field. Deviations of the locally measured cosmic ray spectrum from the average Galactic spectrum are explained by the discrete distribution of the cosmic ray sources in space and time.

Key words. Gamma rays; Star forming regions

1. Introduction

Our knowledge of the properties of Galactic cosmic rays (CRs) is based mostly on the measurements in a single point in the Milky Way galaxy: the position of the Solar system. From these local measurements we know that the spectrum of CRs is an approximate powerlaw with the slope ranging from 2.8 below 200 GeV to 2.6 ... 2.7 in the TeV-PeV energy range, ending with the ”knee” feature above the PeV energy (Olive et al. 2014).

Numerous theoretical models were developed over time to explain the spectral properties of the cosmic ray flux (Berezinskii et al. 1984, Blasi 2013). An implicit assumption of these models is that the approximate 2.7 slope powerlaw spectrum is ”universal”, in the sense that it is valid all over the Milky Way galaxy. The same assumption is commonly adopted in the interpretation of the data on $\gamma$-ray emission from Galactic CR population (Ackermann et al. 2012b) and in the modelling of the extragalactic $\gamma$-ray background produced by a population of star-forming galaxies in the Universe (Ackermann et al. 2012a).

An assumption that the Galactic CR spectrum has the slope 2.7 everywhere across the Galaxy is, however, far from being obvious. None of the theoretical models which "explain" the spectral slope is developed from the first principles. The match between the observed spectral slope and the model calculations is achieved via adjustment of phenomenological parameters, e.g. of the slope of the injection spectrum of CRs in the interstellar medium, $\Gamma_{inj}$ and the modification of the slope by the energy dependent escape of the CRs, characterised by the energy slope of the diffusion coefficient, $\delta$ (Berezinskii et al. 1984). It is well possible that the slope of the locally observed CR spectrum is not identical to that of the average Galactic CR spectrum. Variations of the star formation rate over the last tens of millions of years and discreetness of the cosmic ray source distribution could lead to fluctuations of the shape of the CR spectrum in space and time (Aharonian 2004; Neronov & Semikoz 2012, Kachelriess et al. 2015).

The only possibility for the measurement of the spectrum of CRs at different locations in the Galaxy is via the use of the $\gamma$-ray data (Aharonian 2004; Ackermann et al. 2012b; Neronov et al. 2012). CRs interacting in the interstellar medium (ISM) produce neutral pions which decay into photons. The spectrum of the pion decay $\gamma$-rays has the slope which is nearly identical to that of the parent CR spectrum.
An immediate problem for the measurement of the CR spectrum from the \( \gamma \)-ray data is that the \( \gamma \)-ray flux from the Galaxy contains, apart from the pion decay flux, also the flux produced by the CR electrons via the Bremsstrahlung and inverse Compton mechanisms (Ackermann et al. 2012b). As a consequence, derivation of the \( \gamma \)-ray flux, also the flux produced by the CR electrons, would require a detailed modelling of the three contributions, or a method of separation of the pion decay contribution to the flux from the Bremsstrahlung and inverse Compton contributions.

In what follows we develop a method which allows to separate the pion decay emission from the Bremsstrahlung and inverse Compton emission in the flux coming from the distant parts of the Disk of the Milky Way galaxy. Using this method, we are able to measure the spectrum of cosmic rays at different locations in the Disk, at different distances from the Centre of the Galaxy. We show that the average Galactic CR spectrum in the TeV energy band is harder than the locally observed spectrum of the proton component of the CR flux. We also demonstrate that the average Galactic CR spectrum slope does not vary significantly across the Galaxy and it is also identical to the slope of CRs filling the disk of the Large Magellanic Cloud (LMC) galaxy. This suggests that the measured average slope of the CR spectrum is "universal", in the sense that it is determined by the basic physical laws. It is this slope which could be explained by the straightforward theoretical models of CR injection and propagation.

### 2. Data Analysis

In our work we use 6.7 years of Fermi/LAT data (from August, 4th, 2008 to December 2014). We process the data using the most recent version of the Fermi Science Tools Software v9r33p0 and the P7REP response functions (The Fermi-LAT Collaboration 2013). The spectra of the sources are calculated using two complementary techniques: the binned likelihood analysis and the aperture photometry.

The binned likelihood analysis is based on the fitting of a model of diffuse and point source emission within a "region of interest" to the data. The spatial extent of the region is 13° radius at energies \( \gamma \geq 300 \text{ MeV} \) and 20° radius in the 60-300 MeV energy range. The spatial model includes diffuse Galactic and extragalactic backgrounds and the sources from the 4 year (3FGL) Fermi catalog (The Fermi-LAT Collaboration 2015). In each energy bin we fix the spectral shape of each source to be a power law with index \(-2\). The spectral shapes of diffuse backgrounds are given by the corresponding templates. The normalisations of fluxes of all sources and diffuse backgrounds are treated as free parameters during the fitting.

The aperture photometry method of spectral analysis uses a selection of \( \gamma \)-ray events from pre-defined signal and background regions with the \texttt{gtbin} / \texttt{gtmktime} tools and the calculation of the exposure for the selected regions with the \texttt{gtexposure} tool. All the sources have the spatial extent much larger than the size of the Point Spread Function (PSF) of LAT in the energy range above 1 GeV, where the aperture photometry analysis is performed. Taking this into account, we use the \texttt{gtexposure} tool with the switch \texttt{apcorr=IN} which precludes the correction of exposure for the PSF effects. We remove the contribution of bright point sources to both the signal and background regions by excluding circles of the radius \(0.5°\) around identified pulsars and active galactic nuclei from the Fermi catalog (The Fermi-LAT Collaboration 2013) and around the Galactic Centre source. In the analysis of the signal from the Galactic Plane we explicitly do not remove the unidentified sources from the catalog, because a large fraction of these sources could be just the inhomogeneities of the overall diffuse emission from the ISM. We also do not remove the supernova remnants because they could be considered as a part of the overall \( \gamma \)-ray signal from the interacting Galactic CRs.

### 3. The Galactic Disk

The Galactic diffuse emission is a sum of the pion decay, Bremsstrahlung and inverse Compton contributions. Relative importance of different contributions to the \( \gamma \)-ray flux depends on the photon energy and on the location of the emission region in the Galaxy.

Our goal is to derive a measurement of the spectrum of proton / nuclei CRs residing at different locations in the Galactic Disk from the spectrum of the pion decay emission from the Disk. There are two obvious obstacles for such a measurement. First, the pion decay flux has to be separated from the Bremsstrahlung and inverse Compton fluxes. Next, the flux of the pion decay emission produced at large, several kiloparsecs distances from the Sun has to be separated from the flux of pion decay and inverse Compton / Bremsstrahlung emission form the local interstellar medium.

The spectrum of the Bremsstrahlung is soft and its contribution to the \( \gamma \)-ray flux is negligible in the energy band above \(10 \text{ GeV}\) (Ackermann et al. 2012b). Thus, reducing the energy range of the analysis to \(E_{\gamma} > 10 \text{ GeV}\) should provide a signal which is largely free from the Bremsstrahlung contribution.

The spectrum of inverse Compton emission is harder and the inverse Compton flux could be significant up to the highest energies accessible for the Fermi/LAT. The inverse Compton flux is strongest close to the direction of the Galactic Plane and toward the inner Galaxy, because of the higher density of the interstellar radiation field in the inner part of the Galactic Disk.

Fortunately, the pion decay \( \gamma \)-ray emission is still more concentrated toward the Galactic Plane because its volume luminosity scales with the density of the interstellar gas. The luminosity is falling exponentially with the increase of the altitude above / below the Galactic Plane because the density of the Galactic Disk is falling exponentially with the scale height about 100 pc.

This difference leads to a significant difference of the Galactic latitude profiles of the pion decay and inverse Compton emission (Ackermann et al. 2012b), see Fig. 1 right panel. To separate the pion decay and inverse Compton signals, we take the source signal from a narrow strip \(|b| < 1.5°\) around the Galactic Plane and estimate the background from two narrow strips \(2° < |b| < 3°\) as it is shown in the left panel of Fig. 1. The pion decay emission profile is sharply peaked toward \(b = 0°\), compared to the inverse Compton profile. Integrating the pion decay and inverse Compton fluxes in the \(|b| < 1.5°\) and \(2° < |b| < 3°\) regions one could find that the choice of the source and background regions shown in the left panel of...
The angular extent of the source occupying a 100 pc wide layer around the Galactic Plane is about 10° at the distance 1 kpc from the Sun and is just about 3° for the flux coming from the distances beyond 3 kpc from the Sun position. The highest star formation rate in the Milky Way is in the innermost part of the Galactic Disk at the distances $\geq$ 4 kpc from the Sun. This innermost part of the Galactic Disk spans a strip $|b| < 3°$ on the sky. Choosing both the signal and background regions within a region where the flux from the local ISM does not vary removes the local ISM contribution.

The spectrum of diffuse emission from $|b| < 1.5°$, $|l| < 90°$ strip extracted using the aperture photometry method is shown in Fig. 2. The spectrum above 10 GeV could be fit by a powerlaw with the slope $\Gamma_\gamma = 2.42 \pm 0.03_{\text{stat}} \pm 0.12_{\text{syst}}$. In this energy band the flux is dominated by the pion decay emission. The spectrum could be fitted with a model pion decay spectrum calculated using the code of Kamae et al. (2006) for the powerlaw proton spectrum with the slope $\Gamma_p = 2.45$.

Below 10 GeV the $\gamma$-ray spectrum gets softer. This softening is expected at least due to a non-negligible contribution of the electron Bremsstrahlung to the photon flux. Alternatively, the pion decay spectrum itself could soften below 10 GeV if the CR spectrum gets softer below $\sim 150$ GeV, as does the local CR spectrum. Our analysis method does not allow to distinguish between these two possibilities.

It is not clear a-priori if the average slope of the CR spectrum depends on the distance from the centre of the Galaxy as suggested by Gaggero et al. (2015) or it has a "universal" slope. It is also not clear if the slope depends on the relevant physical parameters like e.g. the star formation rate. Fig. 3 shows the slope of the $\gamma$-ray spectrum of the $|b| < 1.5°$ strip as a function of Galactic longitude. One could see that there is no evidence for the dependence of the slope on the Galactic longitude or, equivalently, on the distance from the Galactic Centre. There is also no correlation between the slope and the overall flux above 10 GeV, as one could see from comparison of the upper and lower panels of Fig. 3.

3.1. Cygnus region

The method of calculation of the pion decay contribution to the diffuse flux from the Galactic Disk developed in the previous section does not work in the outer Galaxy, in the Galactic longitude range $|l| > 90°$. This is because the contribution of the distant parts of the Galactic Disk at several kiloparsecs distances becomes much smaller than the flux from the local ISM. In this case, estimation of the flux from a narrow strip around $b = 0°$ plane catches the degree-scale fluctuations of the flux from the local Galaxy, rather than the flux from the distant parts of the Galactic Disk.

A measurement of the spectrum of CRs in a distant part of the Galactic Disk is still possible in one particular case, namely in the direction of Cygnus region. This direction is tangent to the Galactic arm passing close to the Sun. An enhancement of the diffuse emission from the direction of Cygnus region is commonly attributed to a superposition of the projected $\gamma$-ray emission from the local Galactic arm and the flux produced by the nearby active star formation region at $\sim 1.5$ kpc distance in this direction. Emission
from this nearby star forming region is known to have a hard spectrum with the slope close to $\Gamma_\gamma \simeq 2.2$, supposedly due to a recent injection of freshly accelerated CRs (Ackermann et al. 2011).

The extended emission source in the Cygnus region, reported in the Fermi catalog, is described by a Gaussian spatial template with the width $2^\circ$, shown in Fig. 4. Spectrum of the source with such spatial morphology is shown in Fig. 4. The spectrum above 3 GeV is well described by a power-law with the slope $\Gamma_\gamma = 2.47 \pm 0.09$. This slope is softer than the slope reported by Ackermann et al. (2011), because we have used, contrary to Ackermann et al. (2011), the standard Galactic diffuse emission background for the spectral modelling. In such standard model the extended source in the direction of Cygnus includes the entire emission from the Galactic arm behind the nearby star formation region, rather than only a contribution from the nearby star formation region at 1.5 kpc distance.

As a cross-check, we extract the spectrum of the Cygnus region using the aperture photometry method and taking the source region to be a square box of the size $5^\circ \times 5^\circ$ centered at $l = 80^\circ$, $b = 1^\circ$, see Fig. 4. Similarly to the Galactic Plane spectrum case, we suppress the contribution to the flux from the local interstellar medium and from the inverse Compton emission by an appropriate choice of the Gaussian spatial template (thick data points) and from an $5^\circ \times 5^\circ$ box. Grey dashed line shows a fit with a model of pion decay emission from the powerlaw CR spectrum with the slope $\Gamma_{CR} = 2.45$. Solid grey line shows a powerlaw fit to the box spectrum.

The spectrum of emission from the $5^\circ \times 5^\circ$ box is shown in Fig. 5 by the thin olive colour data points. The slope of the spectrum is $\Gamma_\gamma = 2.42 \pm 0.06$, which is consistent with the slope of the spectrum extracted using the Gaussian template.

The emission from the Cygnus region is dominated by the pion decay flux, as it is clear from the presence of the low-energy cut-off in the spectrum at the pion production threshold $E_\pi \simeq 100$ MeV (Ackermann et al. 2013). The slope of the pion decay spectrum in the Cygnus region is identical to the slope of the spectrum elsewhere in the Galactic Plane. This confirms that the slope $\Gamma_\gamma \simeq 2.42$ is characteristic for the slope of the CR spectrum produced by star formation activity and that it is largely independent of the parameters of the interstellar medium. Indeed, the properties of the interstellar medium in Cygnus region and in the local Galactic arm behind the Cygnus region...
The overall extent of the LMC disk is at least 3° shown in the right panel of Fig. 6 (Gaustad et al. 1999). This is also visible as a bright excess on the Hα map of LMC, see Fig. 6. The brightest emission is detected from the direction of 30 Doradus star forming region, which is consistent with the slope of the spectrum extracted using the aperture photometry method shown by thin data points in Fig. 6. It could be fit by a powerlaw with the slope $\Gamma = 2.39 \pm 0.09_{\text{stat}} \pm 0.07_{\text{syst}}$, which is consistent with the slope of the spectrum extracted using the likelihood analysis.

The overall spectrum in the broad energy range from 60 MeV up to 100 GeV is well fit with a single pion decay component spectrum with the slope of the parent CR spectrum $\Gamma_{CR} = 2.45$, shown by the dashed line in Fig. 7. Contribution of the electron Bremsstrahlung component to the spectrum is constrained by the upper limit in the 60-100 MeV band, where the Bremsstrahlung flux should dominate over the pion decay flux. Similarly to the Galactic Plane and Cygnus region spectra, the Bremsstrahlung flux is negligible in the energy range above several GeV.

The slope of the $\gamma$-ray spectrum of the LMC above 3 GeV is consistent with the slope of the spectrum of $\gamma$-ray emission from the Milky Way disk, see Fig. 8. This suggests that the spectrum of emission from the LMC disk is dominated by the pion decay flux from the proton / nuclei CR interactions in the LMC disk, similarly to the Milky Way emission in the same energy band. This conclusion is supported by the analysis of Foreman et al. (2015) who find that the pion decay flux dominates the $\gamma$-ray emission from the LMC except possibly for the 30 Doradus region where electron Bremsstrahlung and inverse Compton emission could compete with the pion decay emission.

5. Other star forming galaxies

Apart from the Milky Way and LMC, several other normal star forming Galaxies are detected by Fermi/LAT. The conjecture of the universal hard slope of the CR spectrum produced by the star formation should, in principle, hold also for these galaxies.

We have extracted the spectra of the Small Magellanic Cloud and M31 galaxies and checked that the quality of the spectra is not yet sufficient for the measurement of the details of the spectral properties of the CR populations in these galaxies.

6. Discussion

Our analysis of the spectral properties of $\gamma$-ray signal from a 3° wide strip along the Galactic Plane has enabled a separation of the pion decay emission component of the Galactic diffuse emission from the Bremsstrahlung and inverse Compton components in the energy band above 10 GeV. We have used the measurement of the slope of the

**Fig. 6.** Fermi/LAT count map of LMC field in the energy band above 1 GeV (left) compared to the Hα map of LMC (right). Smaller white circle in the left panel shows the extent of the Fermi/LAT Gaussian template for the spatial model of LMC. Larger circle shows the extent of the source signal extraction region for the aperture photometry calculation of the spectrum.

**Fig. 7.** Spectra of the LMC extracted using the likelihood analysis (thick data points) and the aperture photometry method (grey thick / thin data points showing the statistical / systematic errors). Dashed line shows a model fit with the pion decay spectrum produced by the parent proton population with the powerlaw spectrum with the slope $\Gamma_{CR} = 2.45$. Solid line shows a powerlaw fit to the aperture photometry spectrum.
pion decay spectrum to measure the slope of the spectrum of CRs with energies above 100 GeV across the Galactic Disk.

The slope of the Galactic cosmic ray spectrum turns out to be harder than that of the locally measured CR spectrum in the same energy band. The slope of the Galactic CR spectrum does not exhibit significant variations from the inner to outer Galaxy. This points to a “universal” nature of the hard slope, which is largely independent of the local physical conditions in different parts of the Galaxy.

The same hard slope of the CR spectrum is found also in the LMC galaxy. This further supports the conjecture about the “universality” of the hard slope of the spectra of CRs resulting from star formation in galaxies.

The slope of the average CR spectrum derived from our analysis of the Galactic Plane and of the LMC coincides with the slope of the neutrino spectrum in the energy band above 10 TeV, reported by the IceCube collaboration (Aartsen et al. 2012). This suggests that the astrophysical neutrino flux has a contribution from the Milky Way (Neronov et al. 2014, Neronov & Semikoz 2014). A smooth band above 10 TeV, reported by the IceCube collaboration, lies above the slope of the neutrino spectrum in the energy band with the IceCube neutrino spectrum extending up to the PeV energy range indistinguishable to the sub-TeV energy band with the IceCube neutrino spectrum extending up to 2000 GeV. (Aharonian 2004; Kachelriess et al. 2015). In a similar way, a star formation activity episode resulting in formation of a superbubble with an energy output $10^{52}$ erg would change the CR spectrum in a kpc-scale region around it for tens of millions of years (Aharonian 2004; Ahn et al. 2010, Kachelriess et al. 2015).

The slopes of the CR spectra shown in Figs. 2, 3, 5, 7 are the same only because they are derived from the γ-ray spectra of these sources is expected because the dense clumps of the ISM could be situated closer or further from the recent points of injection of CRs (Aharonian 2004, Kachelriess et al. 2015). At the same time, the average-over-the-sources slope of the CR / γ-ray spectra should be close to the average slope of the spectrum of Galactic CRs. This is indeed the case. The average slope of the spectra of sources from the HESS survey is remarkably close to the slope of the spectrum of the $|b| < 1.5^\circ$ strip, $\Gamma_{\text{HESS}} \simeq 2.43$.

The value $\Gamma_{\text{CR}} \simeq 2.45$ of the universal slope of the spectrum of CRs produced by the star formation process could be understood within a straightforward theoretical model, without adjustment of phenomenological parameters. The most commonly considered process of the CR production is the shock acceleration process. This process results in the slope of the injection spectrum of CRs $\Gamma_{\text{inj}} \simeq 2\ldots2.1$ in the most simple settings (Berezinskii et al. 1984, Blandford & Ostriker 1978, Berezhko et al. 1994, Malkov & Drury 2001, Bell & Lucek 2001, Blasi 2013). Propagation of CRs through the turbulent Galactic magnetic field with the subsequent escape of CRs from the Galaxy leads to the softening of the CR spectrum from $\Gamma_{\text{inj}}$ to $\Gamma_{\text{CR}} = \Gamma_{\text{inj}} + \delta$ where $\delta$ is related to the slope of the turbulence power spectrum. It is $\delta = 1/3$ for the Kolmogorov turbulence and $\delta = 1/2$ for the Iroshnikov-Kraichnan turbulence. Measurement $\Gamma_{\text{CR}} \simeq 2.45$ suggests that the injection spectrum of CRs in the ISM has the slope $\Gamma_{\text{inj}} = 2.1$, assuming the Kolmogorov spectrum of the ISM turbulence (Armstrong et al. 1993).

Also straightforward is the understanding of the difference of the slopes of the average Galactic CR spectrum and the CR spectra measurable at fixed locations in the Galactic Disk, like e.g. the measurements at the position of the Solar system. The spectra of CRs measured in any single point typically deviate from the average CR spectrum because they are influenced by the discreteness of the CR source distribution in space and time. A single source which injects about $10^{52}$ erg in CRs could significantly alter the overall energy density of CRs in the local ISM within the region of the volume more than $(0.1 \text{ kpc})^3$ on the time scales of millions of years (Aharonian 2004, Ahn et al. 2010).

The slopes of the CR spectra shown in Figs. 2, 3, 5, 7 are the same only because they are derived from the γ-ray signal collected from sufficiently large regions of the ISM, where the assumptions on the continuity and time independence of the source distribution are valid.

### 7. Summary

We have used the γ-ray data to derive a measurement of the characteristic spectrum of CRs produced by the star formation activity in the Milky Way (Fig. 2) and in the LMC (Fig. 3) galaxies. The slope of the average spectra of CRs in these two galaxies, $\Gamma_{\text{CR}} \simeq 2.45$, is harder than the locally measured spectrum of CRs penetrating in the Solar system. Consistency of the measurement of the slopes of the CR spectra at different locations in the Milky Way Galactic Disk and in the LMC suggests that the spectrum of CRs produced by the star formation activity is universal, i.e. it does not depend on the details of the physical parameters of the star formation process and of the ISM. The value of the universal slope of the CR spectrum is consistent with the straightforward theoretical model of CR injection by the shock acceleration process, which produces the spectrum with the slope $\Gamma_{\text{inj}} \simeq 2\ldots2.1$, followed by the energy-dependent escape of CRs through the turbulent Galactic magnetic field with the ISM turbulence power spectrum. Fluctuations of the slopes of the CR spectra measurable at fixed points in the ISM are attributed to the discreteness
of the CR source distributions and variations of the star formation rate in time.

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