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ON THE *FERMI*-LAT SURPLUS OF THE DIFFUSE GALACTIC GAMMA-RAY EMISSION

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ABSTRACT

Recent observations of the diffuse Galactic γ-ray emission (DGE) by the *Fermi* Large Area Telescope (*Fermi*-LAT) have shown significant deviations, above a few GeV until about 100 GeV, from DGE models that use the GALPROP code for the propagation of cosmic ray (CR) particles outside their sources in the Galaxy and their interaction with the target distributions of the interstellar gas and radiation fields. The surplus of radiation observed is most pronounced in the inner Galaxy, where the concentration of CR sources is strongest. The present study investigates this "*Fermi*-LAT Galactic Plane Surplus" by estimating the γ-ray emission from the sources themselves, which is disregarded in the above DGE models. It is shown that indeed the expected hard spectrum of CRs, still confined in their sources (SCRs), can explain this surplus. The method is based on earlier studies regarding the so-called EGRET GeV excess which by now is generally interpreted as an instrumental effect. The contribution from SCRs is predicted to increasingly exceed the DGE models also above 100 GeV, up to γ-ray energies of about ten TeV, where the corresponding surplus exceeds the hadronic part of the DGE by about one order of magnitude. Above such energies the emission surplus should decrease again with energy due to the finite life-time of the assumed supernova remnant sources. Observations of the DGE in the inner Galaxy at 15 TeV with the Milagro γ-ray detector and, at TeV energies, with the ARGO-YBJ detector are interpreted to provide confirmation of a significant SCR contribution to the DGE.

Subject headings: cosmic rays – diffuse radiation – gamma rays:theory – supernova remnants

1. INTRODUCTION

The diffuse Galactic γ-ray emission (DGE) from the full sky has recently been analyzed and compared with the observations with the *Fermi* Large Area Telescope (*Fermi*-LAT) for high energies (HE; 200 MeV $\leq \epsilon_\gamma \leq$ 100 GeV) (Ackermann et al. 2012). The DGE had been modeled using the GALPROP code (e.g. Moskalenko & Strong 1998; Strong et al. 2000; Porter et al. 2008). For a review, see Strong et al. (2007). These phenomenological models were constrained to reproduce directly measured cosmic ray (CR) data and were then used iteratively to calculate the DGE (e.g. Strong et al. 2004c). To construct a model for the expected total γ-ray emission, the γ-ray emission from the resolved point sources together with the residual instrumental γ-ray background and the extragalactic diffuse γ-ray background – both assumed to be isotropic (Abdo et al. 2010g) – were added to the DGE model. In the inner Galaxy, the emission of the resolved sources apparently reaches a fraction of $\sim$ 50 percent of the expected overall spectral energy flux density at $\epsilon_\gamma \approx$ 100 GeV (Ackermann et al. 2012).

These overall emission models describe the *Fermi*-LAT data well at high and intermediate latitudes and thereby show that the so-called EGRET GeV excess (e.g. Hunter et al. 1997) does not exist in the form previously inferred (Stecker et al. 2008; Abdo et al. 2009a; Ackermann et al. 2012). However, in the Galactic Plane these models systematically underpredict the data above a few GeV, and they do so increasingly above about 10 GeV until 100 GeV (see Fig. 15 of Ackermann et al. 2012). In the present paper this difference between data and model will be called the "*Fermi*-LAT Galactic Plane Surplus" (FL-GPS). It is most pronounced in the inner Galaxy. According to Ackermann et al. (2012), it can however also be seen in the outer Galaxy, with even a small excess at intermediate latitudes[3].

The GALPROP code is constrained by the charged energetic particles directly measured in the neighborhood of the Solar System which are by assumption truly diffuse CRs. Therefore the above discrepancy is not too surprising, because in this comparison the γ-ray emission from particles *within* the CR sources is only taken into account for those γ-ray sources that are resolved by the instrument.

The dominant part of the γ-ray sources resolved by the *Fermi*-LAT, with 1451 items listed in the *Fermi*-LAT 1FGL catalog and taken into account in the Ackermann et al. (2012) analysis, are Pulsars, as far as the Galaxy is concerned. Except for the Crab Nebula and Vela X the HE γ-ray emission from Pulsar Wind Nebulae may actually be again Pulsar radiation, even though most recently three more Pulsar Wind Nebulae have been identified with *Fermi*-LAT (Acero et al. 2013). For purposes of their γ-ray emission these objects are assumed in the present paper to be sources of energetic electrons and positrons, but not sources of nuclear CRs. Of the latter

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[3] An uncommented overprediction of the models can be seen in the energy interval between 10 and 100 GeV for the polar cap region south in Fig. 13 of the same authors. This apparent discrepancy is characterized by a gamma-ray flux that is more than an order of magnitude smaller than in the inner Galaxy and varies in an irregular way in energy. Due to this aspect of the data, the discrepancy will not be discussed in the sequel.

presumably only a handful have been resolved, and are thus included in the overall *Fermi*-LAT emission model (Ackermann et al. 2012). In all probability the majority of nuclear CR sources remains unresolved, and is therefore excluded from that model. As a consequence the FL-GPS can be expected to be a physical, not an instrumental effect.

Independently of whether they are resolved or not, the nuclear CR sources are presumably concentrated in the Galactic disk, if they are the consequence of star formation processes. They are assumed in the present paper to be the shell-type supernova remnants (SNRs), regardless whether they are isolated or embedded in stellar associations, e.g. in Superbubbles. The fact that the FL-GPS is concentrated in the inner Galaxy is then the result of the well-known concentration of SN explosions in the inner Galaxy (e.g. Case & Bhattacharya 1998) and in the inner parts of other galaxies (Dragicevich et al. 1999). This concentration is also confirmed by the Galactic distribution of Pulsars as compact remnants of core-collapse SN explosions (Lorimer 2004). The total γ-ray emission does not have such a strong radial gradient in the Galactic Plane, as observed at comparatively low energies were the purely diffuse emission should dominate, by e.g. the COS-B satellite for $\epsilon_\gamma > 150$ MeV (Strong et al. 1988) and the EGRET instrument on the CGRO satellite for 100 MeV $< \epsilon_\gamma < 10^4$ MeV (Strong & Mattox 1996; Digel et al. 1996). This difference has also been discussed by Paul (2001).

A weak gradient of the diffuse emission has been interpreted theoretically as the consequence of preferential (faster) convective CR removal from the disk into the halo in the inner Galaxy, where the higher CR source density and the decrease of the Galactic escape velocity with increasing Galactic radius drive a faster *Galactic Wind* (Breitschwerdt et al. 2002). This is a nonlinear propagation effect. Therefore the concentration of the FL-GPS in the inner Galaxy is largely the result of the radial gradient in the CR source density, because the diffuse CR density is largely independent of radius[4].

The dependence of the FL-GPS on γ-ray energy is another aspect which is suggested to be due to the difference between the diffuse particle spectra and the particle source spectra. In a selfconsistent model for energetic particle propagation in such a Galactic Wind (Ptuskin et al. 1997), where nonlinear damping of the scattering magnetic irregularities balances their growth due to the outward CR streaming, this spectral difference is naturally explained.

The theoretical interpretation of the location of the FL-GPS in the Galaxy and of its energy dependence, presented here, is therefore entirely based on the *propagation characteristics of the diffuse CR population in the Galaxy*, both in its dependence on the radial distance from the axis of rotation as well as in its variation with particle energy.

From a purely phenomenological point of view it is only necessary to assume that the DGE is essentially independent of radius in the Galactic Plane and that the diffuse energy distribution of the charged energetic particles is significantly softer than the energy distribution in their sources. Indeed, starting with the work of Juliusson et al. (1972) on the decrease of the flux ratio of secondary to primary nuclear particles with increasing rigidity, as observed in the neighborhood of the Solar System, the particle energy spectra inside these sources have been inferred to be substantially harder than the energy spectrum of the average CRs in the Interstellar Medium (ISM) (see e.g. Ptuskin 2012, for a recent review). Even though the volume fraction of the active sources is presumably quite small, the energy density of the energetic particles there is very high, coexisting together with a thermal gas density comparable to that in the average ISM. In this context an active source is meant to be one which still basically contains the particles it has accelerated. These particles shall be called source cosmic rays (SCRs). As demonstrated for the first time in Berezhko & Völk (2000), the contribution of SCRs to the DGE from accelerated CRs - still confined in their parent SNRs - progressively increases with energy due to their hard spectrum. Therefore this contribution becomes unavoidably significant the latest at VHE energies. In a subsequent paper the SCR contribution was studied in more detail (Berezhko & Völk 2004). For the following these papers will be referred to as BV00 and BV04, respectively. A later study of the contribution of unresolved source populations has been made by Strong (2007).

Shell-type SNRs have been observed, especially at very high energy (VHE; $\epsilon_\gamma \geq 100$ GeV), to be important sources of γ-rays (e.g. Hinton & Hofmann 2009). It is less clear, in which phase of their lifetime they lose most of the accelerated particles. This is determined by a complex interplay of the dissipation of magnetic field fluctuations inside (e.g. Ptuskin & Zirakashvili 2003, 2005) and the hydrodynamic break-up of the overall expanding SNR shell.

The shell-type SNRs are not the only VHE γ-ray sources in the Galaxy. In fact, the most abundant resolved Galactic γ-ray sources at VHE are Pulsar Wind Nebulae (PWN) (e.g. de Oña-Wilhelmi et al. 2013). These are in all probability the result of the winds from young, energetic Pulsars with characteristic ages $\lesssim 10^5$ yrs, and of the accelerated population of electrons in them which, in particular, emit inverse Compton (IC) γ-rays in an almost calorimetric fashion (de Oña-Wilhelmi et al. 2013). The particle acceleration and resulting emission is quite complex and poorly understood. PWN observations, including the radio and X-ray range, are often fitted by a phenomenological model going back to Aharonian & Atoyan (1999) which assumes an energy distribution of the radiating electrons in the form of a power law with a cutoff, in a uniform magnetic field and in a radiation field approximately equal to the Cosmic Microwave Background (CMB) (e.g. Abramowski et al. 2012). The γ-ray spectral energy densities of PWNs are therefore assumed to be typically peaked with a cutoff at a few TeV. The lifetime $\tau_{\rm PWN}$ of TeV emitting leptons in typical PWNs has been estimated to be $\sim$ 40 kyr (de Jager & Djannati-Atai 2009). In a rough sense the total number $N_{\rm PWN}$ of PWNs in the Galaxy is then

[4] A physically different interpretation has been advanced in terms of a compensatory radial increase of the $W_{\rm CO}$-to-$N({\rm H}_2)$ scaling factor, regarding the gas target for the gamma-ray emission, on account of a radial decrease of the metallicity in the Galactic disk inferred from observations in external galaxies (Strong et al. 2004c).

$N_{\rm PWN} \sim 800(\tau_{\rm PWN}/40{\rm kyr})(\nu_{\rm PWN}/2)$, where $\nu_{\rm PWN}$ denotes the Galactic VHE-emitting PWN rate in units of core collapse events per century (de Oña-Wilhelmi et al. 2013). This is at least as large as the number of active shell-type SNRs (see below). As a result the population of unresolved PWNs may contribute to the FL-GPS, and substantially to the total VHE emission, even though this is difficult to estimate for the reasons given above.

The relative size of the contributions of the unresolved parts of the various γ-ray source populations is an important question. Presumably at energies beyond about 10 TeV the PWN fraction is small due to the cutoff in the electron spectra as a result of radiative losses. The spectra of nuclear particles in shell-type SNRs can, on the other hand, extend to energies of many hundreds of TeV with differential energy spectra close to a power law $\epsilon^{-\gamma}$, where $2.0 \lesssim \gamma \lesssim 2.2$. Such an extent in energy is in particular expected in young objects, like the type Ia objects SN1006 (Berezhko et al. 2012) or Tycho's SNR (Berezhko et al. 2013), where the escape of the highest-energy particles is arguably still weak. In very energetic, young core collapse supernovae, γ-ray energies well in excess of 100 TeV might be reached (Bell et al. 2013). However, the corresponding Supernova rate is expected to be so low (Ptuskin et al. 2013) (less than about 1% of the total Supernova rate) that their contribution is disregarded here.

In this paper only the contribution of unresolved shell-type SNRs to the Galactic γ-ray emission will be discussed in detail, following the earlier work by BV00 and BV04. As will be shown, the radiation from these SCRs which extends with a hard power-law-type energy spectrum to multi-TeV γ-ray energies can readily explain the above-mentioned FL-GPS and predicts its monotonic increase from $\epsilon_\gamma \sim 100$ GeV into the multi-TeV region. The evaluation of the contribution of the unresolved PWN population is left for a future study.

2. EXTRAPOLATION OF THE EXPECTED OVERALL *FERMI*-LAT EMISSION MODEL BEYOND 100 GEV

The *Fermi*-LAT overall emission model corresponds to a spectral energy distribution (SED) $I_{\rm tot} = I_{\rm DGE} + I_{\rm RS} + I_{\rm IB}$, where $I_{\rm DGE}$ denotes the sum of the truly diffuse hadronic plus inverse Compton plus Bremsstrahlung emission spectra, $I_{\rm RS}$ is the contribution from the resolved sources, and $I_{\rm IB}$ corresponds to that of the isotropic backgrounds. The resolved sources – which include few shell-type SNRs, many Pulsars, and, at energies $\epsilon_\gamma \gtrsim 100$ GeV, the resolved PWNs – are expected to have a harder spectrum than the DGE. Therefore $I_{\rm tot}$ corresponds to a harder spectrum than the approximate $\epsilon_\gamma^{-2.75}$-dependence of the modeled DGE in the inner Galaxy at energies $\epsilon_\gamma \gtrsim 10$ GeV below any cutoff. To a large degree this is due to the contribution of the IC component and especially, that of the resolved sources.

Given the representation by the Fermi-LAT collaboration, the most reasonable initial extension beyond 100 GeV of $I_{\rm tot}$ appears to be an extrapolation by a power-law distribution $I_{\rm tot} \propto \epsilon_\gamma^{-\gamma}$ of the same spectral index γ which it has between $\epsilon_\gamma \sim 10$ GeV and 100 GeV. However, the γ-ray spectral energy densities of PWNs are assumed to be typically peaked with a cutoff at several TeV. The truly diffuse leptonic emission is expected to cut off at similar energies. Therefore the component $I_{\rm tot} - I^{\pi}_{\rm GCR}$ is multiplied by an exponential term $\exp(-\epsilon_\gamma/1\ {\rm TeV})$. $I_{\rm tot}$ extrapolated in this form is shown by the dashed curve in Fig.1[5]. From its construction $I_{\rm tot}$ is an approximate lower limit to the expected SED without unresolved sources.

The program of the present paper is then to calculate the contribution of the unresolved shell-type SNRs in order to predict a lower limit to the total emission in the inner Galaxy in the GeV range and above. As will be shown, this lower limit implies an increasing discrepancy between measured and expected "diffuse Galactic emission' in the region of few GeV $< \epsilon_\gamma <$ 100 GeV, and thus can explain the FL-GPS. The discrepancy is predicted to increase up to energies ~ 10 TeV in the VHE range. Beyond that γ-ray energy the contribution of the unresolved shell-type SNRs goes down due to energy dependent escape of CRs from shell-type SNRs that makes for a shorter confinement time of CRs with higher energy.

3. RESULTS AND DISCUSSION

In Fig.1 a calculated γ-ray spectrum $I_\gamma = I_{\rm tot} + I_{\rm SCR}$ of the low latitude inner Galaxy ($-80^\circ < l < 80^\circ$, $|b| \le 8^\circ$) is presented. Besides the overall emission model $I_{\rm tot}$, discussed in the previous section, it includes the contribution $I_{\rm SCR}$ of SCRs confined within unresolved SNRs. The SCR contribution is calculated based on the approach developed in BV04:

$$I_{\rm SCR} = I^{\pi}_{\rm GCR} R (1 + R_{\rm ep}),$$

where R depends on the Galactocentric distance as a result of the non-uniform distribution of the Galactic SNRs (see Introduction). $I_{\rm SCR}$ comprises the π^0-decay component due to hadronic SCRs $I^{\pi}_{\rm SCR} = I^{\pi}_{\rm GCR} R$ and the inverse Compton (IC) component due to electron SCRs $I^{\rm IC}_{\rm SCR} = I^{\pi}_{\rm GCR} R R_{\rm ep}$. Here $I^{\pi}_{\rm GCR}$ is chosen as the π^0-decay component due to hadronic GCRs. At γ-ray energy $\epsilon_\gamma < 100$ GeV the quantity $I^{\pi}_{\rm GCR}(\epsilon_\gamma)$, determined by Ackermann et al. (2012), and its power law extrapolation $I^{\pi}_{\rm GCR} \propto \epsilon_\gamma^{-2.75}$ to higher energies $\epsilon_\gamma > 100$ GeV is used.

The dimensionless ratio $R = I^{\pi}_{\rm SCR}/I^{\pi}_{\rm GCR}$ according to BV04 has the form

$$R(\epsilon_\gamma) = 0.07 \frac{N_{\rm g}^{\rm SCR}}{N_{\rm g}^{\rm GCR}} \left(\frac{T_{\rm p}}{10^5\ {\rm yr}}\right) \left(\frac{\epsilon_\gamma}{1\ {\rm GeV}}\right)^{0.6}, \qquad (1)$$

where $N_{\rm g}^{\rm GCR}$ and $N_{\rm g}^{\rm SCR}$ are the gas number density in the Galactic disk and inside SNRs, respectively. The first factor in this expression, $N_{\rm g}^{\rm SCR}/N_{\rm g}^{\rm GCR}$, represents the ratio of target nuclei for the two populations of CRs. The second factor, $T_{\rm p}$, represents the fact that the number of SNRs, wich confine SCRs with energy ϵ, is proportional to $T_{\rm p}(\epsilon)$. The third factor $\epsilon_\gamma^{0.6}$ is due to the harder SCR spectrum compared with the GCR spectrum.

Contrary to the earlier considerations of BV00 and BV04, where the interior SNR magnetic field was assumed to be time independent, the proton confinement time $T_{\rm p}(\epsilon \approx 10\epsilon_\gamma)$ inside the expanding SNR is determined taking into account magnetic field amplification

[5] Admittedly, this procedure disregards other possible resolved sources, like γ-ray binaries, which may reach significantly higher γ-ray energies beyond 10 TeV (e.g. Aharonian et al. 2006).

and its time dependence $B \propto (\rho V_S^2)^{1/2} \propto t^{-3/5}$. Magnetic field amplification in strong shocks is a general theoretical concept arising from the expected nonlinear growth of unstable magnetic irregularities produced by the accelerating CRs themselves (Bell 2004). Field amplification is however also clearly observed in a number of SNR sources (e.g. Völk et al. 2005). Here it is assumed to be a universal effect in shell-type SNRs (e.g. Bell et al. 2013). In this case the maximum energy of SCR protons, accelerated at a given SNR evolutionary epoch, decreases with time according to the relation $\epsilon \propto BR_S V_S \propto t^{-4/5}$. This leads to the following expression for the proton confinement time

$$T_p = \min\{T_{SN}, t_0(\epsilon/\epsilon_{max})^{-5/4} \text{ yr}\}, \qquad (2)$$

where T_{SN} is the time until which SNRs can confine the main fraction of accelerated particles, ϵ_{max} is the maximal energy of protons that can be accelerated in SNRs, achieved at the beginning of the Sedov phase $t = t_0$. The decrease of the proton confinement time T_p with energy ϵ is due to the diminishing ability of the SNR shock to produce high-energy CRs during the Sedov phase, which implies the escape of the highest energy CRs from the SNR (Berezhko & Krymsky 1988; Berezhko 1996; Berezhko et al. 1996). Therefore the description in terms of the escape time T_p is equivalent to an initial production of the SCR spectrum $N_{SCR} \propto \epsilon^{-\gamma}$ for $mc^2 < \epsilon < \epsilon_{max}$ in the evolving SNR, following the SN explosion proper. Subsequently this spectrum is confined over the time-scale $T_p(\epsilon)$. This weighs the fraction of the highest energies ϵ_{max} with the Sedov time t_0, lower-energy particles with a larger time that increases with decreasing ϵ, and "low-energy" particles with T_{SN}.

Note that, due to the considerably harder SCR energy spectrum compared with the GCR spectrum, the factor $R \propto \epsilon_\gamma^{0.6}$ grows with energy up to a maximal energy $\epsilon_\gamma^* \approx 0.1\epsilon_{max}(t_0/T_{SN})^{4/5}$ of γ-rays produced by SCRs confined in SNRs for the whole active evolutionary time $T_p = T_{SN}$. The spectrum $I_{SCR}(\epsilon_\gamma)$ at $\epsilon_\gamma < \epsilon_\gamma^*$ is predominantly produced by SNRs of ages $t \approx T_{SN}$. Therefore it is only weakly sensitive to the details of SNR evolution at the epochs $t < T_{SN}$. At higher energies $\epsilon_\gamma > \epsilon_\gamma^*$, the ratio $R \propto \epsilon_\gamma^{0.6-5/4}$ goes down with energy and the SCR contribution decreases due to the decrease of the confinement time T_p.

The ratio $R_{ep} = I_{SCR}^{IC}/I_{SCR}^{\pi}$ is calculated as described in BV04 with a time-independent interior magnetic field value $B = 30$ μG.

Since the dominant part of SNRs in our Galaxy is due to type II SNe with a relatively low progenitor star mass, which do not form extended wind bubbles during their evolution, here only the contribution of SNRs expanding into a uniform ISM will be considered.

The calculations presented in Fig.1 have been performed with the following values of the relevant physical parameters: sweep up time $t_0 = 10^3$ yr, confinement time of SCRs inside SNRs $T_{SN} = 3 \times 10^4$ yr, electron to proton ratio $K_{ep} = 10^{-2}$, effective SCR power law index $\gamma = 2.15$, and 10 percent efficiency of SCR production in SNRs[6]. Since the SCRs are confined inside the SNRs within a thin shell behind the shock, where also the shock-compressed ISM gas is situated, the interior SNR gas number density $N_g^{SCR} = 4N_g^{GCR}$ is used, where N_g^{GCR} is the ISM gas number density. Since during the last ten years convincing observational evidence of considerable SNR magnetic field amplification (Völk et al. 2005) leading to the production of CRs with energy up to $\epsilon_{max} \approx 2 \times 10^6$ GeV (Berezhko & Völk 2007) has been found, the value $\epsilon_{max} = 2 \times 10^6$ GeV is used here. It is considerably larger compared with BV00 and BV04.

Due to the cutoff introduced for the component $I_{tot} - I_{GCR}^{\pi}$ the calculated SED $\epsilon_\gamma^2 I_\gamma$ represents a lower limit for the expected γ-ray background at energies $\epsilon_\gamma > 1$ TeV. It should nevertheless be emphasized here that I_{SCR}/I_{GCR}^{π} is given in terms of the ratios $I_{SCR}^{\pi}/I_{GCR}^{\pi}$ and $I_{SCR}^{IC}/I_{GCR}^{\pi}$, and that I_{GCR}^{π} is determined by the diffuse nuclear CR distribution which is rather well-known at least until the "knee" of the all-particle GCR spectrum. Therefore I_{SCR} does not depend on the form of the extrapolation of I_{tot} beyond 100 GeV.

As demonstrated in BV04 there are two physical parameters which significantly influence the expected γ-ray emission from the ensemble of shell-type SNRs: the CR confinement time T_{SN} and the mean magnetic field strength B inside the SNRs. For a conventional value $B = 10$ μG the expected γ-ray flux from SNRs exceeds the HEGRA upper limit considerably if the SCR confinement time is as large as 10^5 yr. The contradiction can be resolved either if one suggests an appreciably higher postshock magnetic field $B \gtrsim 30$ μG or if the SCR confinement time is as small as $T_{SN} \sim 10^4$ yr. These possibilities can be attributed to field amplification by the SCRs themselves. In fact, nonlinear field amplification may also lead to a substantial decrease of the SCR confinement time: according to Ptuskin & Zirakashvili (2003) maximal turbulent Alfvén wave damping with its corresponding increase of CR mobility could make the SCR confinement time as small as $T_{SN} \sim 10^4$ yr.

The only physical parameter which strongly influences the IC γ-ray production rate for given synchrotron emission rate is the SNR magnetic field B: $I_{SCR}^{IC} \propto B^{-2}$. Due to the high magnetic field $B = 30$ μG the overall contribution of the hadronic SCRs to the γ-ray flux dominates over that of the electron SCRs: at TeV-energies $I_{SCR}^{IC} \approx 0.3 I_{SCR}^{\pi}$.

As shown in Fig.1, the discrepancy between the observed "diffuse" intensity and standard model predictions at energies above a few GeV (Ackermann et al. 2012) can be attributed to the SCR contribution alone up to ~ 100 GeV.

Unfortunately, existing VHE measurements do not coincide well in their longitude (l) and latitude (b) coverage with the corresponding ranges for *Fermi*-LAT that correspond to $-80^\circ < l < +80^\circ$ and $-8^\circ < b < +8^\circ$. Therefore the following comparisons must be taken with reservations, and for this reason the observational results from these measurements are indicated in grey

[6] Although theoretical calculations lead to a harder particle spectrum, $\gamma \leq 2.0$, the choice of an effective $\gamma = 2.15$ for the SCR γ-ray -production allows the approximate inclusion of HE γ-ray emission from localised strong gas density enhancements overrun by the SNR shock, as one might interpret SNR-associated γ-ray emissions observed, limited largely to the HE range (e.g. Ackermann et al. 2013; Giordano et al. 2012; Berezhko et al. 2013).

color in Fig.1 1.: As one can see, the expected γ-ray flux at $\epsilon_\gamma = 1$ TeV is consistent with the HEGRA upper limit, the Whipple upper limits (Reynolds et al. 1993; LeBohec et al. 2000), the Tibet-AS upper limits (Amenomori et al. 2005), and with the fluxes measured by the Milagro detector (Abdo et al. 2009a) at $\epsilon_\gamma = 15$ TeV, as well as with those obtained with the ARGO-YBJ detector (Ma et al. 2011) in the TeV range, taken at face value[7].

4. CONCLUSIONS

These considerations demonstrate that the SCRs inevitably make a strong contribution to the "diffuse" γ-ray flux from the Galactic disk at all energies above a few GeV, if the population of shell-type SNRs is the main source of the GCRs. This explains the *Fermi*-LAT Galactic Plane Surplus. The quantitative estimates show in addition that the SCR contribution dominates over the extrapolated Fermi-LAT model for the total diffuse emission - which includes detected sources and isotropic Backgrounds - at energies greater than 100 GeV due to its substantially harder spectrum. The diffuse emission measured by Milagro at 15 TeV and by ARGO-YBJ at TeV energies provide limited evidence for that. It will be interesting to see if, and then to which extent, TeV observations will show an even higher total emission than the one calculated here. If this was the case it is suggested that such a difference should be attributed to the emission from Pulsar Wind Nebulae, or even to other particle sources, some of which were mentioned above. A full consideration of the potential particle sources is beyond the scope of this paper.

The Galactocentric variation of any surplus over the purely diffuse emission above a few GeV should correspond to the Galactocentric variation of the ratio R between the π^0-decay components of source cosmic rays and truly diffuse Galactic cosmic rays as a result of the observed SNR distribution. This implies a concentration in the inner Galaxy.

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[7] Even though the Milagro flux refers to a smaller longitude interval than used in the present paper, it also refers to a smaller latitude range, so that these effects tend to cancel to lowest order. See however the above general reservations on the comparability of these data.

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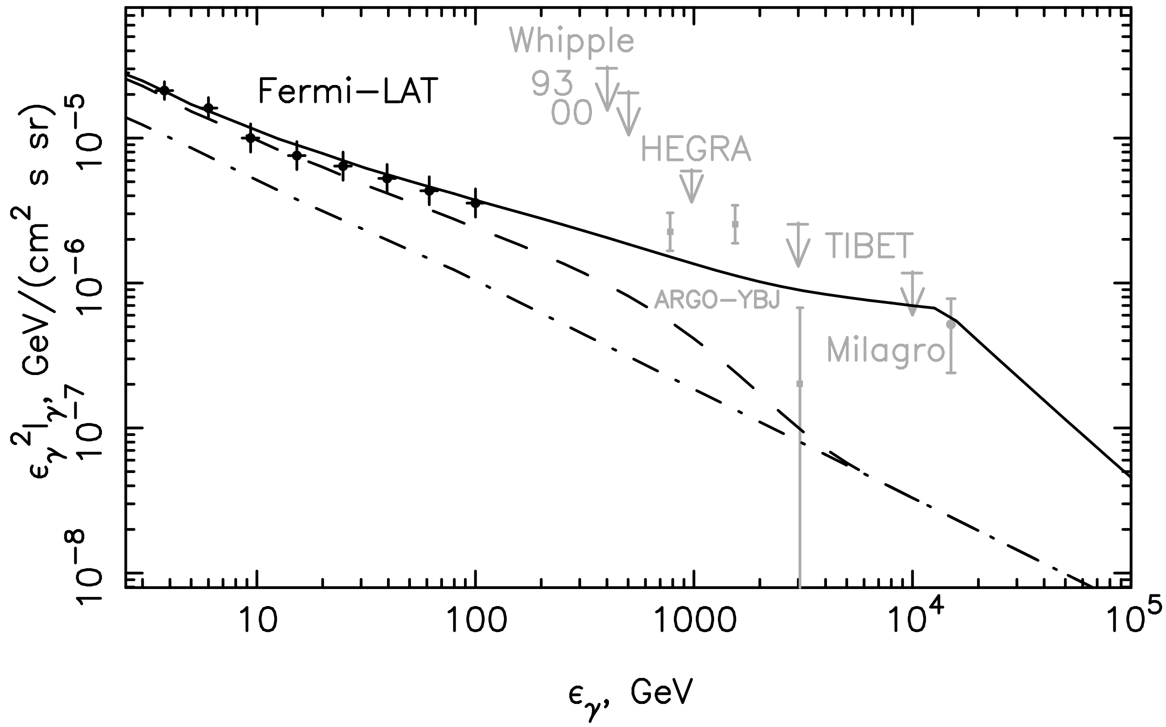

FIG. 1.— The diffuse γ-ray spectrum of the low latitude inner Galaxy ($-80° < l < 80°$, $|b| \leq 8°$). The expected π^0-decay γ-ray component $I^{\pi}_{\rm GCR}$ created by truly diffuse GCRs in the Galactic Disk is shown by the dash-dotted line. The total expected emission $I_{\rm tot}$ (= modeled diffuse Galactic emission $I_{\rm DGE}$ plus detected sources and isotropic backgrounds) up to $\epsilon_\gamma = 100$ GeV (Ackermann et al. 2012) corresponds to the dashed line. This $I_{\rm tot}$ is extrapolated beyond 100 GeV by a power law with an assumed cutoff in $I_{\rm tot} - I^{\pi}_{\rm GCR}$ (see text). The solid line represent the total expected emission including the contribution of SCRs confined inside unresolved SNRs. The *Fermi*-LAT data (Ackermann et al. 2012) are shown in black color. ARGO-YBJ data in the TeV range (Ma et al. 2011), Milagro data at $\epsilon_\gamma = 15$ TeV (Abdo et al. 2009a), the Wipple upper limits (Reynolds et al. 1993; LeBohec et al. 2000), the HEGRA upper limit (Aharonian et al. 2001), and the Tibet upper limits (Amenomori et al. 2005) at $\epsilon_\gamma = 3$ and 10 TeV, are shown in grey color, see text. The vertical error bars of the *Fermi*-LAT data points correspond to the thickness of the gray region which includes systematic error in Fig. 15 of Ackermann et al. (2012).

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