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Common solution of three cosmic puzzles

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Summary. — We show that the observed fluxes, spectra and sky distributions of the diffuse backgrounds of high energy astronomical neutrinos, gamma rays and cosmic ray positrons observed near Earth satisfy the simple relations expected from their common production in hadronic collisions of high energy cosmic ray nuclei with diffuse matter in/near source.

1. – Introduction

The origin of the neutrino background radiation (NBR) above 35 TeV discovered with IceCube [1], of the sub-TeV Galactic cosmic ray (CR) positrons measured recently with PAMELA, Fermi-LAT and AMS [2] and the TeV gamma-ray background (GBR) measured with Fermi-LAT [3] are still unsolved cosmic puzzles. High energy particle physics offers three main mechanisms, which can produce simultaneously high energy neutrinos (ν's), gamma rays (γ's) and positrons (e^+'s): 1) meson production in hadronic collisions of high energy CRs with diffuse matter in the interstellar medium of galaxies [4] in the intergalactic medium (IGM) of Galaxy clusters [5], or inside the cosmic ray sources [6], 2) photo production of mesons in CR collisions with radiation in/near γ-ray sources [7], and 3) decay of massive dark matter particle [8] relics from the Big Bang.

If the main origin of the observed very high energy astronomical γ-rays, neutrinos and positrons is the decay of mesons produced in high energy CR collisions with diffuse matter in/near the CR sources, and/or in the ISM, and/or in the IGM, then under very general assumptions their fluxes, spectra and sky distributions are simply related [9]. These relations are summarized briefly below and are confronted with the observations of the high energy gamma ray background radiation (GBR) by Fermi-LAT [3], the neutrino background radiation (NBR) by IceCube [1] and the cosmic ray positrons by AMS [2]. They demonstrate that the observed high energy NBR, GBR, and the cosmic ray positrons satisfy the simple relations expected from hadronic production of mesons by high energy cosmic rays in collisions with diffuse matter. They imply similar sky distributions of the NBR and GBR where Galactic contribution dominates the flux, in particular at low latitudes. We also show that the flux of the high energy CR positrons observed near Earth with PAMELA and AMS2 is that expected from secondary production of mesons in the local ISM by the flux of cosmic ray nucleons (protons and nucleons bound in atomic nuclei) observed near Earth.

2. – CR production of secondaries

The local flux of high energy cosmic ray nucleons (which will be denoted by p here on) between several GeV and the cosmic ray knee energy $E_{\rm knee} \approx 1\,{\rm PeV}/$nucleon is well described by

$$\Phi_p(E) \approx C\,(E/{\rm GeV})^{-\beta}\ {\rm fu}, \tag{1}$$

where $C \approx 1.8$, $\beta \approx 2.70$ [10] and fu $= 1/({\rm GeV\ cm^2\ s\ sr})$ is the flux unit. Between the CR "knee" and CR ankle at $E \sim 3\,{\rm EeV}$, $C \approx 114$, and $\beta \approx 3.0$ [11]. We will ignore the small differences between CR protons and nucleons bound in CR nuclei (A, Z) at the same energy per nucleon, because such nucleons contribute only a few percents to the total CR p flux and most of them are bound in very light nuclei whose inelastic cross section per nucleon is $\sim \sigma_{{\rm pA}/A} \approx \sigma_{\rm pp}$, *i.e.*, roughly the same as that of free protons.

CRs escape their production sites by diffusion through turbulent magnetic fields. For a Kolmogorov spectrum [12] of random magnetic fields, their escape time satisfies $\tau_{\rm esc}(E) \propto E^{-1/3}$. In a steady state, the supply rate of high energy CR protons by galactic CR sources (s) is equal to their escape rate from the galaxy. Hence, the injection rate of CR nucleons by CR sources satisfies $J_{\rm p} \propto \Phi_{\rm p}/\tau_{\rm esc} \propto E^{-\beta_{\rm s}}$ where $\beta_{\rm s} = \beta - 1/3$. Roughly, $\beta_{\rm s} = \beta - 1/3 \approx 2.37$ for $E < E_{\rm knee}(p)$, which is consistent with Fermi acceleration modified by escape by diffusion, and $\beta_{\rm s} \approx 2.67$ for $E_{\rm knee}(p) < E < E_{\rm ankle}(p)$.

Hadronic collisions of high energy CR nuclei of energy E per nucleon in diffuse matter of baryon density n produce γ-rays, ν's and $e^\pm$'s mainly through π and K decays. If the lab frame energy of a secondary particle is a fraction x of the nucleon energy E and if the distribution of x is independent of E (Feynman scaling [13]), then to a good approximation, a flux $\Phi_{\rm p} \propto E^{-\beta}$ of CR nucleons produces through hadronic collisions in a diffuse matter secondary γ-rays, ν's, and $e^\pm$'s with a flux per unit volume [14]

$$\Phi_{\rm i}(E) \propto \sigma_{\rm in}\, n\, c\, F_{\rm i}(\beta)\, \Phi_{\rm p}(E), \tag{2}$$

where i $= \gamma$, ν, or $e^\pm$, $\sigma_{\rm in} \approx 30 \times (E_{\rm p}/{\rm GeV})^{0.058}\,{\rm mb}$ is the pp total inelastic cross section, and $F_{\rm i}(\beta) = \langle x_{\rm i}^{\beta-1}\rangle$ where the averaging is over the Feynman x distribution of particle i in the inclusive production pp $\to$ iX. Since the secondary γ-rays, $e^\pm$'s and ν's are produced by the same CR sources, their production ratios are simply the ratios of their $F_{\rm i}(\beta)$'s. These ratios are later modified by propagation effects: the oscillations of neutrinos in space that spread the neutrino flux over the three neutrino flavors, the attenuation of high energy γ-rays mainly by Compton scattering and pair production on background photons, and the energy losses of high energy electrons and positrons through synchrotron radiation and inverse Compton scattering of background photons while they are diffusing through the turbulent magnetic fields of their host galaxies.

The contribution of electron bremsstrahlung and inverse Compton scattering of photons to the GBR becomes relatively small above $\sim 100\,{\rm GeV}$ compared to the contribution from hadronic CR production of π^0's [9]. Neutrinos are produced mainly through the decay of charged pions and Kaons. As long as the neutrinos and gamma-rays are produced mainly through inclusive π decays by CRs with energy below the CR knee whose in/near source spectral index is $\beta_j \approx 2.7 - 1/3 - 0.06 \approx 2.31$, their fluxes satisfy

$$\Phi_\nu(E) \approx (m_{\pi^+}/2\, m_{\pi^0})^{1.31}\, \Phi_\gamma(E) \approx 0.39\, \Phi_\gamma(E), \tag{3}$$

per ν flavor. At TeV energies K decay contribution to the flux of neutrinos becomes significant, and hadronic π and K meson production by cosmic rays in/near source, where $\beta_j \approx 3 - 1/3 - 0.06 \approx 2.61$, yield [9] per ν flavor

$$\Phi_\nu(E) \approx 0.52\, \Phi_\gamma(E). \tag{4}$$

Equations (3), (4), cannot be tested directly with current data because they neglect the attenuation of high energy γ-rays, and because the NBR was measured at $E_\nu > 30\,\mathrm{TeV}$, while the published Fermi-LAT data on the GBR and on the extragalactic gamma background are limited to $E < 1.2\,\mathrm{TeV}$ (see fig. 1(a), (b)) (other measurements of the high energy GBR with Cherenkov telescopes, such as those with H.E.S.S around 15 TeV and in the ARGO-YBJ experiment around 1 TeV, were limited to the Galactic plane $|b| < 2^\circ$).

The attenuation of Galactic γ-rays of energy below TeV is negligible, while the observed extragalactic γ-ray background (EGB) is strongly absorbed above 100 GeV. The full sky GBR measured with Fermi-LAT in the energy range 100 GeV–2 TeV can be corrected for the attenuation of the EGB and used in eq. (3) to predict Φ_ν in this energy range, and then it can be extrapolated to the energy range of the NBR detected with IceCube using $\phi_\nu(E) \propto \sigma_{\rm in}((1+z)\, 20\, E)\, \Phi_s((1+z)\, 20\, E)$, which follows from eq. (1) for extragalactic CR sources. In this relation, $1 + z \approx 2.5 \pm 0.5$ is the redshift at the peak of star formation rate (*i.e.*, of supernova explosions and GRBs) and of the evolution function of the emission by BL Lac objects —presumably the main extragalactic sources of high energy CRs.

Equations (1), (3) and (4) predict that the non attenuated EGB behaves like $\mathrm{E}^{-2.31}$ well below 50 TeV. Indeed, the EGB measured with Fermi-LAT below 820 GeV was best fit with an exponential cutoff power-law [3]

$$\Phi_{\rm EGB} \approx (6.42 \pm 0.40) \times 10^{-7}\, (E/\mathrm{GeV})^{-2.30\,\pm\,0.02}\, e^{-E/E_c}\, \mathrm{fu}, \tag{5}$$

where $E_c \approx 366 \pm 100\,\mathrm{GeV}$ ($\chi^2/\mathrm{df} = 6.9/23$). This best fit is shown in fig. 1(a). Presumably, this power-law represents well the unattenuated EGB produced by high energy cosmic rays with energies below the "knee".

Equations (1), (3) yield $\phi_\nu \approx 1.03 \times 10^{-11}\,\mathrm{fu}$ per ν flavor at $E = 100\,\mathrm{GeV}$ whose extrapolation to $E > 50\,\mathrm{TeV}$ yields an isotropic extragalactic [EG] neutrino flux per ν flavor,

$$E^2\, \Phi_\nu[\mathrm{EG}] \approx (0.85 \pm .30) \times 10^{-8} \left[\frac{E}{100\,\mathrm{TeV}}\right]^{-0.61\,\pm\,.05} \mathrm{GeV}^2\,\mathrm{fu}. \tag{6}$$

Similarly, the Galactic [MW] contribution $E^2\, \Phi_\gamma[\mathrm{MW}] = E^2\, (\Phi_{\rm GBR} - \Phi_{\rm EGB}) \approx 2.49 \times 10^{-7}\,\mathrm{GeV}^2\,\mathrm{fu}$ to the GBR at $E = \mathrm{TeV}$ and eq. (3) can be used to estimate $\Phi_\nu[\mathrm{MW}]$, which can be extrapolated to $E > 50\,\mathrm{TeV}$, yielding

$$E^2\, \Phi_\nu[\mathrm{MW}] \approx (2.62 \pm .20) \times 10^{-8} \left[\frac{E}{100\,\mathrm{TeV}}\right]^{-0.61\,\pm\,.05} \mathrm{GeV}^2\,\mathrm{fu} \tag{7}$$

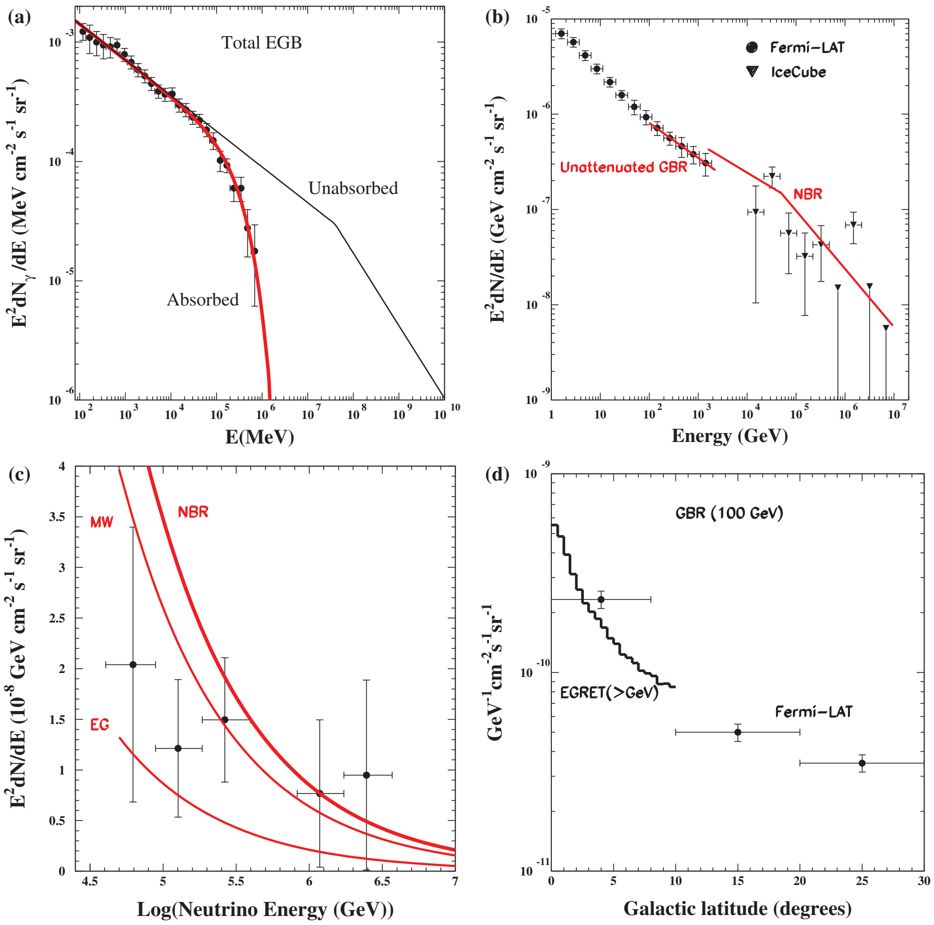

Fig. 1. – Top left (a): The extragalactic gamma-ray background (EGB) that was measured by Fermi-LAT [3] and the best fit exponentially cutoff power-law. The straight line represents the unabsorbed power-law EGB. Top right (b): The NBR (all flavors) above 20 TeV as measured by IceCube [1] compared to that expected from the unattenuated GBR below 2 TeV, inferred from the observed GBR and EGB by Fermi-LAT [3]. Bottom left (c): The NBR (per ν flavor) above 50 TeV as measured by IceCube [1], compared to that expected from the GBR and EGB, measured by Fermi-LAT [3]. The separate contributions of extragalactic (EG) neutrinos and Galactic (MW) neutrinos to the NBR are also shown. Bottom right (d): The sky distribution of the high energy GBR as function of Galactic latitude, observed with Fermi-LAT at 100 GeV and with EGRET aboard the Compton Gamma Ray Observatory at $E > 1\,\mathrm{GeV}$ [15] normalized to the Fermi-LAT distribution. The NBR is predicted to have nearly the same sky distribution as that of the unattenuated high energy GBR.

per ν flavor. The predicted energy flux of the NBR (all flavors) obtained from the "unattenuated GBR",

$$E^2\,\Phi_\nu \approx (1.04 \pm 0.15) \times 10^{-7} \left[\frac{E}{100\,\mathrm{TeV}}\right]^{-0.61\,\pm\,.05} \mathrm{GeV}^2\,\mathrm{fu}, \tag{8}$$

is compared in fig. 1(b) to the all-flavors NBR measured with IceCube (Aartsen *et al.* 2015). The separate contributions of the Milky Way ($\approx 76\%$) and extragalactic sources ($\approx 24\%$) to the NBR are shown in fig. 1(c). Assuming the all flavors NBR flux to be isotropic, its best fit single power-law between 25 TeV and 2.8 PeV by the IceCube collaboration [1], $E^2\,\Phi_{\rm NBR} \approx (6.69 \pm 1.20) \times 10^{-8}\,(E/100\,{\rm TeV})^{-0.50\,\pm\,.09}\,{\rm GeV}^2\,{\rm fu}$, is in rough agreement with eq. (8).

The sky distribution of the NBR measured with IceCube is expected to coincide with that of the unattenuated high energy GBR, which is roughly that measured by Fermi-LAT at 100 GeV. This distribution that is peaked sharply around the Galactic center is shown in fig. 1(d). Its peak, however, subtends only a small solid angle: The GBR that was measured with Fermi-LAT near 100 GeV [3] suggests that only $\sim$4.2% of the neutrino events point back towards the Galactic center within latitudes $-8^\circ \leq b \leq +8^\circ$ and longitudes $-80^\circ \leq l \leq +80^\circ$, which cover only $\approx 0.43\%$ of the full sky. Also plotted are the sky distribution of the GBR at $E > 1\,{\rm GeV}$ measured with EGRET aboard the Compton Gamma Ray Observatory [15] and normalized to the flux measured by Fermi-Lat at 100 GeV. The diffuse γ-ray emission (flux and sky distribution) from the Galactic plane ($0^\circ < b < 2^\circ$) and from point sources measured at higher energies with buried muon detectors (*e.g.*, CASA-MIA), water Cherenkov detectors (*e.g.*, Milagro and HWAC) and atmospheric Cherenkov detectors (*e.g.*, H.E.S.S., MAGIC, and VERITAS), are generally consistent within errors with that extrapolated from the Fermi-LAT GBR assuming $\Phi_\gamma(E) \propto E^{-2.30}$ modified by attenuation in the Galactic and extragalactic background light.

3. – Cosmic ray positrons near Earth

A detailed derivation of the expected flux of high energy cosmic ray positrons near Earth produced in hadronic interactions of cosmic ray nucleons in the local ISM, and its comparison to the flux measured with high precision by the AMS2 collaboration [2] is presented in [16]. Here, we summarize it briefly.

In a steady state, the local flux $\Phi_{\rm e^+}(E)$ of e$^+$'s produced in the ISM satisfies

$$\frac{{\rm d}}{{\rm d}E}[b(E)\,\Phi_{\rm e^+}(E)] = J_{\rm e^+}(E), \tag{9}$$

where $b(E) = -{\rm d}E/{\rm d}t$ is the loss rate of e$^+$ energy by radiation (rad) and by escape (esc) from the Galaxy by diffusion through its turbulent magnetic fields, and

$$J_{\rm e^+}(E) \approx F_{\rm e^+}\,\sigma_{\rm in}({\rm pp})\,n_{\rm ism}\,c\,\Phi_{\rm p} \tag{10}$$

is the local production rate of CR positrons in the ISM whose nucleon density in the solar neighborhood is $n_{\rm ism}$. The solution of eq. (9) is

$$\Phi_{\rm e^+}(E) \approx F_{\rm e^+}\,\sigma_{\rm in}({\rm pp})\,n_{\rm ism}\,c\,\tau_{\rm e}\,\Phi_{\rm p}(E)/(\beta_j - 1), \tag{11}$$

where $\Phi_{\rm p}$ is given by eq. (2), $n_{\rm ism} \approx 0.9\,{\rm cm}^{-3}$ in the solar neighborhood $K_{\rm e^+} \approx 7 \times 10^{-3}$ for $\beta_j \approx 2.7 - 0.06 = 2.64$ and $\tau_{\rm e} = E/({\rm d}E/{\rm d}t)$ is the mean life-time of positrons in the ISM due to their escape from the Galaxy by diffusion (${\rm d}E/{\rm d}t \sim -E/\tau_{\rm esc}$) and radiative energy losses (inverse Compton scattering of background photons and synchrotron radiation). It satisfies $1/\tau_{\rm e} = 1/\tau_{\rm esc} + 1/\tau_{\rm rad}$, *i.e.*, $\tau_{\rm e} = \tau_{\rm esc}\,\tau_{\rm rad}/(\tau_{\rm esc} + \tau_{\rm rad})$. For random

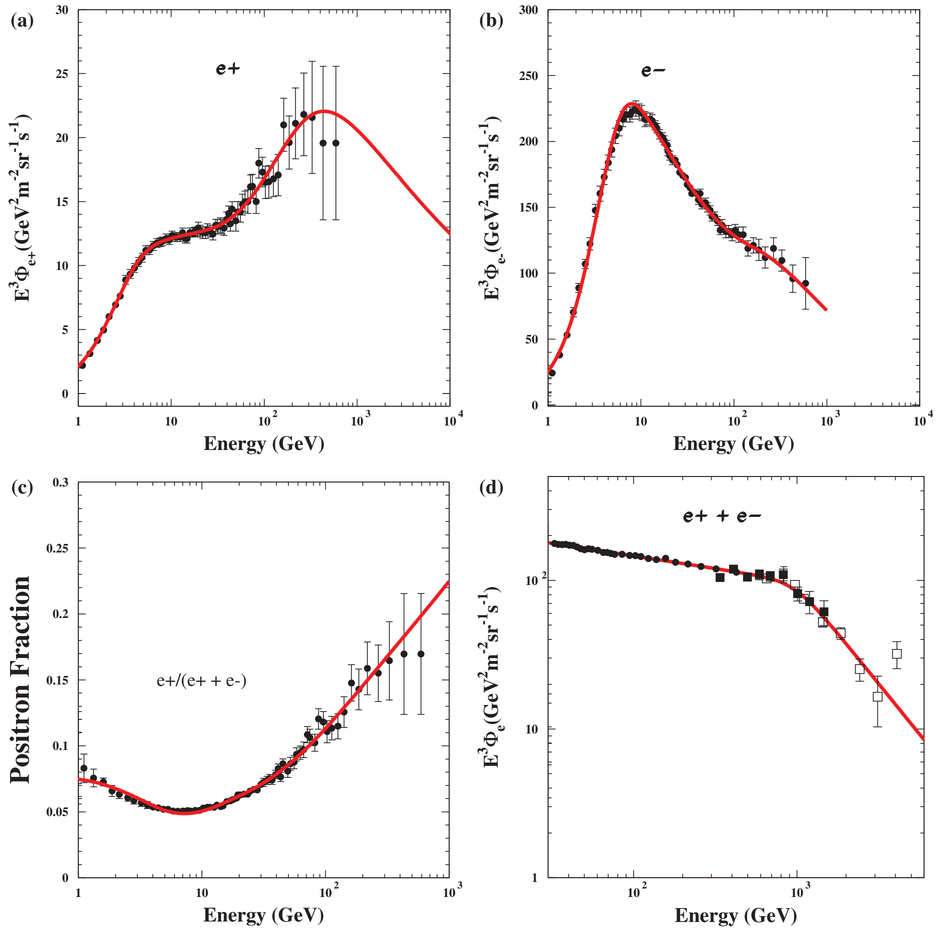

Fig. 2. – Top left (a): Comparison between the high-energy e^+ CR flux measured with AMS2 [2] and the secondary e^+ flux expected from hadronic interactions of the primary CR nucleons in the local ISM. Top right (b): Comparison between the flux of high-energy e^- CRs measured with AMS2 [2] and the flux expected from Fermi acceleration in source of e^-'s plus secondary production in/near source and in the ISM [16]. Bottom left: Comparison between the positron fraction measured with AMS2 [2] and the positron fraction expected from CR interactions in the local ISM [16]. Bottom right (d): Cutoff power-law fit [16] to the combined high-energy $e^\pm$ flux measured near Earth with AMS (full circles) [2] and with H.E.S.S (squares) [19]. The normalization of the H.E.S.S data was adjusted within their estimated systematic error to match the more precise AMS2 data below TeV.

Galactic magnetic fields with a Kolmogorov spectrum

$$\tau_{\rm esc} \approx 7.5\times 10^{14}\,(E/{\rm GeV})^{-1/3}\,{\rm s} \tag{12}$$

where the normalization has been adjusted to the value obtained from a leaky box model analysis of the flux ratio ^{10}Be/^{9}Be measured with the Cosmic Ray Isotope Spectrometer (CRIS) in the energy range 70–145 MeV/nucleon [17].

The radiative life time due to synchrotron emission in the local ISM magnetic field with energy density $U \approx B^2/8\pi \approx 0.40\,{\rm eV/cm^3}$ and inverse Compton scattering of the local background photons (diffuse Galactic light (DGL) with energy density $U \approx 0.41\,\mathrm{eV/cm^3}$, far infra red (FIR) light with $U \approx 0.40\,\mathrm{eV/cm^3}$, and cosmic microwave background (CMB) with $U \approx 0.26\,\mathrm{eV/cm^3}$), was calculated in the Thomson and Klein Nishina regimes following the approximations introduced in [18]. Other energy loss mechanisms that are important only at energy well below 10 GeV (Coulomb scattering, ionization and bremsstrahlung) as well as threshold effects, geomagnetic shielding and solar modulation, were included for completeness through a best fit phenomenological depletion factor $D(E) = 1 - \exp(-(E/V)^\alpha)$, which is time-dependent but does not affect the behavior at $E > 10\,\mathrm{GeV}$.

In fig. 2(a), the flux measured with AMS2 is compared to the expected local flux of CR e^+'s as given by eq. (11) where $F_{\mathrm{e}^+}\,\Phi_\mathrm{p}(E)$ has been replaced by $\Phi_\mathrm{p}(E/\bar{x}_{\mathrm{e}^+})/\bar{x}_{\mathrm{e}^+}$ with the CR proton flux measured with AMS2 [2]. For completeness, we show in fig. 2(b) the CR e^-'s flux expected from Fermi acceleration of e^-'s in source plus secondary production in/near source and in the ISM [16] and the positron fraction (fig. 2(c)).

4. – CR $\mathrm{e}^\pm$ knee near TeV?

The energy spectrum of high energy $\mathrm{e}^\pm$ CRs measured with H.E.S.S. [19] suggests a sharp break in the combined $\mathrm{e}^\pm$ spectrum near $E \sim$ TeV. This is shown in fig. 2(d) where we plotted a smooth cutoff power-law fit to the combined $\mathrm{e}^\pm$ flux [16] measured with AMS2 [2] and with H.E.S.S [19]. A cutoff/break is expected when the radiative life time of the primary e^- CRs becomes shorter than their travel time by diffusion from their source to Earth. However, for the main Galactic sources, this cutoff is much below the H.E.S.S. break/cutoff. The H.E.S.S. cutoff could have been a DM signal, but it can also be explained by standard astroparticle physics such as:
A. Reacceleration cutoff when the reacceleration time in the Galactic ISM exceeds the electrons' lifetimes due to their radiative energy losses and escape from the Galaxy by diffusion.
B. CR e^- "knee" at $E_\mathrm{knee}(\mathrm{e}^-) = (m_\mathrm{e}/m_\mathrm{p})E_\mathrm{knee}(\mathrm{p}) \approx 1\,\mathrm{TeV}$ in the spectrum of e^- CRs, which are Fermi-accelerated together with protons and nuclei by the highly relativistic jets launched in SNeIc [20].

REFERENCES

[1] IceCube Collaboration (Abbasi R. *et al.*), *Astrophys. J.*, **732** (2011) 18; The IceCube Collaboration (Aartsen M. G. *et al.*), *Science*, **342** (2013) 1242856; *Phys. Rev. Lett.*, **113** (2014) 101101; **114** (2015) 171102.

[2] PAMELA Collaboration (Adriani O. *et al.*), *Nature*, **458** (2009) 607; *Astropart. Phys.*, **34** (2010) 1; *Phys. Rev. Lett.*, **111** (2013) 081102; Fermi-LAT Collaboration (Ackermann M. *et al.*), *Phys. Rev. Lett.*, **108** (2012) 011103; AMS Collaboration (Aguillar M. *et al.*), *Phys. Rev. Lett.*, **110** (2013) 141102; AMS Collaboration (Accardo L. *et al.*), *Phys. Rev. Lett.*, **113** (2014) 121101; Ting S., CERN Colloquium, 18.09.2014 AMS Collaboration press release `http://press.web.cern.ch/press-releases/2014/09`.

[3] The Fermi-LAT collab. (Abdo A. A. *et al.*), *Phys. Rev. Lett.*, **104** (2010) 101101; Fermi-LAT Collaboration (Ackermann M. *et al.*), *Astrophys. J.*, **750** (2012) 3; **799** (2015) 86.

[4] See, *E.g.,* Stecker F., *Astrophys. J*, **228** (1979) 919; Dar A., *Phys. Lett. B*, **159** (1985) 1985; Dar A., *Am. Inst. Phys.*, **222** (1990) 497; Berezinsky V. *et al.*, *Astropart. Phys.*,

1 (1993) 281; Loeb A. and Waxman E., *JCAP*, **05** (2006) 003. Evoli C., Grasso D. and Maccione L., arXiv:1310.5123; and references therein.

[5] Dar A. and Shaviv N. J., *Phys. Rev. Lett.*, **75** (1995) 3052.

[6] Production of positrons in hadronic interactions of cosmic rays inside/near their sources was suggested in Dado S. and Dar A., *Mem. Soc. Ast. It.*, **81** (2010) 132 [arXiv:0903.0165] to explain the rising positron fraction discovered with PAMELA [2]. See also Blasi P., *Phys. Rev. Lett.*, **103**, 051104 (arXiv e-print:0903.2794); Stawarz L., Petrosian V. and Blandford R. D., *Astrophys. J.*, **710** (2010) 236, arXiv e-print:0908.1094.

[7] Mannheim K., *Phys. Rev. D*, **48** (1993) 2408; Learned J. G. and Mannheim K., *Ann. Rev. of Nuc. & Part. Sci.*, **50** (2000) 679; Anchordoqui L. *et al.*, *J. High Ener. Phys.*, **1-2** (2014) 1, and references therein.

[8] Bergstrom L., *New J. Phys.*, **11** (2009) 105006. For a recent review see, *e.g.* Ibarra A., Tran D. and Weniger C., *Int. J. Mod. Phys. A*, **28** (2013) 1330040, and references therein.

[9] Dado S. and Dar A., *JHEAP*, **9-10** (2016) [arXiv:1505.04988] and references therein.

[10] PDG (Olive K. A. *et al.*), *Chin. Phys. C*, **38** (2014) 090001.

[11] KASCADE-Grande Collaboration (Apel W. D. *et al.*), *Phys. Rev. D*, **87** (2013) 081101.

[12] Kolmogorov A., *Dokl. Akad. Nauk SSSR*, **30** (1941) 301, reprinted in *Proc. R. Soc. London A*, **434** (1941) 9.

[13] Feynman R. P., *Phys. Rev. Lett.*, **23** (1969) 1415.

[14] Dar A., *Phys. Rev. Lett.*, **51** (1983) 227; Dar A., *Phys. Lett. B*, **159** (1985) 205.

[15] Pohl M. *et al.*, *Astrophys. J.*, **49** (1997) 159 [astro-ph/9706151].

[16] Dado S. and Dar A., *Astrophys. J.*, **812** (2015) 38.

[17] Lipari P., 2014, arXiv:1407.5223.

[18] Schlickeiser R. and Ruppel J., *NJP*, **12** (2010) 033044 [arXiv:0908.2183].

[19] H.E.S.S. Collaboration (Aharonian F. *et al.*), *PRL*, **101** (1998) 261104; *A&A*, **508** (1999) 561.

[20] Dar A. and De Rújula A., *Phys. Rep.*, **466** (2008) 179.