

ON THE e^+e^- EXCESSES AND THE KNEE OF THE COSMIC RAY SPECTRA—HINTS OF COSMIC RAY ACCELERATION IN YOUNG SUPERNOVA REMNANTS

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Received 2009 April 22; accepted 2009 June 15; published 2009 July 16

ABSTRACT

Supernova remnants (SNRs) have long been regarded as sources of the Galactic cosmic rays (CRs) up to petaelectronvolts, but convincing evidence is still lacking. In this work we explore the common origin of the subtle features of the CR spectra, such as the knee of CR spectra and the excesses of electron/positron fluxes recently observed by ATIC, H.E.S.S., *Fermi*-LAT, and PAMELA. Numerical calculation shows that those features of CR spectra can be well reproduced in a scenario with e^+e^- pair production by interactions between high-energy CRs and background photons in an environment similar to the young SNR. The success of such a coherent explanation serves in turn as evidence that at least a portion of CRs might be accelerated in young SNRs.

Key words: acceleration of particles – cosmic rays – supernova remnants

Since the discovery made by Kulikov & Kristiansen (1958), the knee of the cosmic ray (CR) spectra observed ~ 4 PeV has remained a puzzle for half a century. The origin of the knee has become a key problem of CR physics, as it is closely related to the acceleration of the Galactic CRs. There have been extensive studies on the issue (e.g., see the review of Hörandel 2006 and references therein); however, no consensus has been reached yet due to the lack of high-precision experimental information.

Recently, the ATIC experiment measured the cosmic electron (electron and positron) spectrum up to several TeV (Chang et al. 2008) with high precision and showed evidence for an obvious excess of flux above tens of GeV. In addition, the ground-based atmospheric Cerenkov telescope H.E.S.S. and the space satellite *Fermi*, which are dedicated to high-energy γ -ray detection, also reported their results on the electron spectrum measurements (Abdo et al. 2009; Aharonian et al. 2008, 2009). Despite some discrepancies between the results of those experiments, all of them seem to show the excess of electrons compared with the background estimation. At the same time, the PAMELA experiment also published their results on positron fraction for energies up to ~ 100 GeV (Adriani et al. 2009). The PAMELA results show clear positron excess, in agreement with the anomaly observed before by balloon-borne experiments (Barwick et al. 1997; Aguilar et al. 2007).

It is suggested that the rise of the positron fraction may require a primary source of e^+e^- pairs (Serpico 2009). As early as the 1990s, Aharonian & Atoyan (1991) proposed a model involving the e^+e^- pair production mechanism from the interactions between high-energy γ -rays and optical or ultraviolet radiation in the vicinity of discrete sources, to explain the electron/positron excesses from early time balloon-borne experiments. We think that it might be more probable to explain the lepton excess by the e^+e^- pair production via interactions between CRs and background photons. Such a process would be much more efficient than the $\gamma\gamma$ interaction because the cross sections are comparable, while in the former case multiple collisions are allowed.

In addition to the production of e^+e^- pairs, the interaction between nuclei and background radiation will unavoidably change the spectrum of CRs on the source and may lead to the formation of the knee. Considering the radiation at the source is

at the optical energy level ($\sim eV$), we expect the pair production to occur at ~ 1 PeV for protons and a few PeV for helium, which just corresponds to the “knee” of CR spectra. In the rest frame of CR nuclei, the secondary electrons/positrons have energies around MeV, which turn out to be about TeV in the laboratory frame. It is striking to note this is just the energy range where the excesses have been observed by ATIC, *Fermi*, and H.E.S.S. As for the energy budget, the energy density of the excess electrons observed by ATIC is about 3×10^{-5} eV cm⁻³ between 0.1 and 1 TeV, which is of the order of CR energy loss assuming a spectral break from -2.7 to -3.1 at energy ~ 1 PeV.³ It can be seen that the interaction between CR nuclei and background photons naturally bridges the knee of CR spectra and the excesses of electrons/positrons.

It is generally believed that the Galactic CRs are accelerated by the shock waves in supernova remnants (SNRs). We will focus on the acceleration of CRs by the neutron star inside the shell of young SNRs for our purpose, because that is where abundant high-energy CRs (projectile) and background photons (target) can be found. As described in Gaisser et al. (1987), Berezhinskii & Ginzburg (1987), and Gaisser et al. (1989), the CRs up to ultra high energies (e.g., 10^{18} eV) can be accelerated in a very short period (\sim yr or shorter) after the explosion of the supernova. The radiation field has an initial temperature of about several thousand K, which is equivalent to a photon energy of $\sim eV$. Before the radiation field decays and the temperature cools down in hundreds of days, the e^+e^- pair production process can occur many times for one CR particle. As both the magnetic field and radiation field are very strong in the case of young SNRs, the electron energy cannot exceed a few TeV because of the synchrotron depletion and the inverse Compton scattering. It is worth noting that there should also be energy gain for electrons through acceleration. As shown in Vannoni et al. (2009), the electron acceleration in radiation-dominated environments should exhibit a pile-up spectrum around the cutoff energy, which should be a few TeV in the case of young SNRs (Gaisser 1990). The properties of young SNRs seem to

³ Note that this estimate is based on the observational spectra. The energy density of CRs at the source will be much larger than that needed of the excess electrons due to the fact that the diffusion time of PeV CRs is shorter than the energy loss time of TeV electrons in propagation.

fit well with what is required to understand the knee of CR spectra and the abnormal spectra of electrons/positrons, but a quantitative study is necessary.

For simplicity we decouple the acceleration and interaction processes in the calculation, i.e., the nuclei are first accelerated to very high energies and then they interact in the photon field. Finally, we inject the nuclei and electrons/positrons in the Galaxy to calculate the propagation effect and derive the observational spectra on the Earth. The Monte Carlo (MC) method is used to calculate the energy losses of the nuclei and the energies of the generated e^+e^- pairs.

There are three processes of interactions between CRs and photons, i.e., pair production, photodisintegration, and photo-production. The cross sections for pair production and photodisintegration are given in Blumenthal (1970) and Puget et al. (1976), respectively. The pion production cross section for protons is adopted from Amsler et al. (2008), and we employ an $A^{0.91}$ dependence for other nuclei with atomic number A (Stanev et al. 1985).

We choose a power-law spectrum with index about 2 for primary CRs, according to the *Fermi* acceleration mechanism (Gaisser 1990). The actual spectral index of the three main components—proton, helium and iron—are slightly tuned in the calculation to match the data. For other nuclei which do not play a significant role we adopt the parameterization $\gamma_Z = a + bZ - 0.6$ with the fitting parameters $a = 2.69$ and $b = -2.07 \times 10^{-3}$ (Hörandel 2003). Here the 0.6 subtraction from parameter a is done to explicitly take into account the propagation correction from the observations to the source spectra (see below). The relative abundances of various kinds of nuclei after propagation are normalized to the fluxes at 1 TeV given in Hörandel (2003). The propagation effects of nuclei are approached using a leaky-box model. The escape time for CR nuclei is taken as $\tau_{\text{esc}}(R) \approx 2 \times 10^8 \left(\frac{R}{1 \text{GV}}\right)^{-0.6}$ yr, where $R = p/Z$ is the rigidity of nuclei. This relation is fitted from the low-energy B/C data (Putze et al. 2009) and we extrapolate it directly to the PeV energy range.

As for the radiation field around the source, the temperature evolution with time is a crucial factor to define the dominant type of interactions between CRs and background photons. In a simple case, the temperature remains unchanged when CRs are being accelerated to ultra high energies. The three types of interactions may then happen simultaneously. However, this may not be true provided that the threshold energies of photodisintegration and pion production are much higher than that of pair production. The pair production should start earlier and slows down the acceleration of CRs, which makes the other two processes with higher thresholds more difficult to occur. The observational data actually support this argument. As shown by the dashed lines in the upper two panels of Figure 1, if we allow the photodisintegration to be active when fitting the helium spectrum, we find that protons are overproduced and the calculated proton spectrum does not agree with the data. The suppression of photodisintegration can be understood by considering that the radiation field decays and/or cools down rapidly (Gaisser et al. 1987; Berezhinskii & Ginzburg 1987; Gaisser et al. 1989) compared to the timescale of the CR acceleration. This leaves only the pair production as the main interaction between CRs and radiation photons. Therefore, in the following calculation, we forbid the photodisintegration and pion production and consider only pair production.

Based on the previous considerations, the temperature and effective photon density are fitted to the observed spectra of

Table 1
Parameter Settings in the Monte-Carlo Calculation

Species	T_{ph} (K)	$\langle n\sigma\tau \rangle$ (10^{29} cm^{-2})	$\hat{\tau}$ (yr)	γ_Z
Proton	1×10^4	8.1	0.04	2.14
Helium	7×10^3	12.9	0.19	2.02
Iron	2×10^3	0.9	0.58	2.03

individual elements. As shown by the solid lines in Figure 1, the calculated spectra of proton, helium, iron, and all the particle CRs agree well with the measurements. In Table 1, the parameters used in the simulation are summarized: the temperature, the effective column density of photon and interaction time assumed in a blackbody radiation field, and the initial power-law index of each element. In this work we assume the second knee (~ 300 PeV) of the CR spectra is due to the interaction between iron and background photons but this assumption is not a mandatory one (see below the discussion on systematic check). The temperatures and photon densities of other nuclei are derived using a linear interpolation with respect to the atomic number A between helium and iron. The heavy nuclei (low charge over mass ratio) correspond to low temperatures because they need longer time to be accelerated to reach the pair production threshold when the temperature of the source has decreased. It can also be seen from Table 1 that if the photon field is as intense as a blackbody radiation, an interaction time from a few weeks to a few months is enough to produce the observed spectrum distortion.

The generated spectra of electrons/positrons at the source location for individual nuclei and all CRs are shown in Figure 2. The propagation effect of electrons/positrons in the Galaxy has to be considered to determine the spectrum on Earth. Unlike CRs, the dominant effect for electron propagation is the energy losses due to inverse Compton scattering and synchrotron radiation at energies higher than ~ 10 GeV. In this work the GALPROP code (Strong & Moskalenko 1998) is used to calculate the propagation of electrons and positrons.

As shown by the lower thick lines in Figure 2, the propagated electron spectrum becomes softer due to the cooling effects from energy losses. It is, however, still harder than the experimental data. But as pointed out in Gaisser et al. (1989), the high energy tail ($\gtrsim 1$ TeV) of electrons could be depleted in the environment of young SNR by the strong magnetic and radiation fields. An accurate calculation needs to involve a detailed modeling of radiation, interaction, and acceleration. As this work focuses on the interaction rather than the acceleration and radiation of electrons, we will simply adopt an exponential cutoff on the injection spectra of electrons/positrons with a value experimentally suggested by H.E.S.S. measurements (Aharonian et al. 2008). The low curves in Figure 2 show the effects of different values of cutoff energy on the electron spectrum.

The calculated (e^+e^-) spectrum and the positron fraction for a cutoff energy $E_c \approx 2$ TeV are shown by the thick lines in Figure 3 together with the observational data. The calculated flux of (e^+e^-) is scaled to match the data by a free normalization factor (quantitatively, it is $\sim 3\%$ for this model configuration). This parameter represents the dissipation and escape probability of electrons/positrons in the source region. In Figure 3, the term “bkg” represents the standard background contribution of primary electrons and secondary electrons/positrons from CR interactions with the interstellar medium. For the background

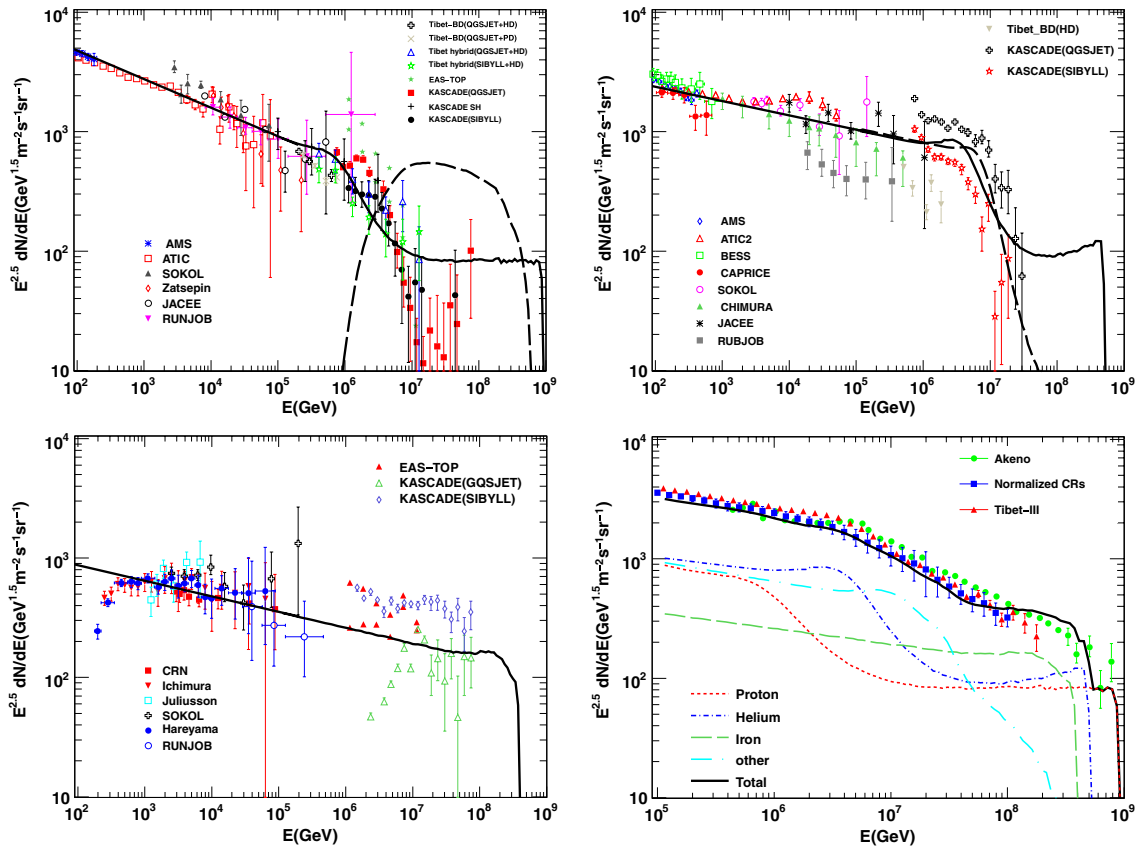


Figure 1. Solid lines in each figure are the calculated energy spectra for protons, helium, iron, and total CRs, respectively, after including the pair production interactions with photons. The dashed lines in the upper two panels are helium spectrum with pair production, photodisintegration and pion production, and the secondary proton spectrum due to photodisintegration of helium. Observational data are—proton: Tibet hybrid (Amenomori et al. 2006), Tibet-BD (Amenomori et al. 2000), JACEE (Asakimori et al. 1998), RUNJOB (Apanasenko et al. 2001), KASCADE (Antoni et al. 2005, 2004), EAS-TOP (Navarra 2003), ATIC (Ahn 2003), Zatsepin (Zatsepin et al. 1993), SOKOL (Ivanenko et al. 1993), AMS (Alcaraz et al. 2000), JACEE (Asakimori et al. 1998), KASCADE (Antoni et al. 2005), Tibet-BD (Amenomori et al. 2000), ATIC2 (Panov et al. 2007), RUNJOB (Apanasenko et al. 2001), SOKOL (Ivanenko et al. 1993), Ichimura (Ichimura et al. 1993), BESS (Haino et al. 2004), AMS (Aguilar et al. 2002), CAPRICE (Boezio et al. 2003); iron: EAS-TOP (Navarra 2003), KASCADE (Antoni et al. 2005), Juliusson (Juliusson 1974), Ichimura (Ichimura et al. 1993), CRN (Mueller et al. 1991), Hareyama (Hareyama 1999), RUNJOB (Apanasenko et al. 2001), SOKOL (Ivanenko et al. 1993); total: Tibet-III (Amenomori et al. 2008a), Akeno (Nagano et al. 1984). The normalized data are derived by combining all data with a rescale based on the extrapolation of the direct measurements (Hörandel 2003).

calculation, we use the diffusion + convection (DC) model (Yin et al. 2009) with parameters tuned to be consistent with the low-energy CR data. For background electrons at the high energy end (\sim TeV) we implement the same exponential cutoff as described above. The results show good agreement with the observational data by, e.g., ATIC and PAMELA. Furthermore, by slightly adjusting the background and a 20% decrease of the generated $e^+ + e^-$ flux, the *Fermi*, H.E.S.S., and PAMELA data can also be well fitted simultaneously, as shown by the thin lines in Figure 3.

As a systematic check, while still assuming that pair production is the dominant interaction between CRs and photons, a constant source temperature is tried to reproduce the observed spectra. We find that the calculated spectra are also in agreement with the observational data for temperatures from 5000 K to 7000 K.

In summary we propose to explain the features of the CR spectra by the e^+e^- pair production at the acceleration sources in an environment similar to the young SNRs. We show that the spectra of CRs and electrons/positrons agree well with the observations. This in turn provides a strong support that at least a portion of CRs might be accelerated in young SNRs. Our work provides a new interpretation to understand the abnormal positron fraction observed by PAMELA and the electrons excesses by ATIC/*Fermi* in the standard astrophysical framework. In addition, we can note in our model that only

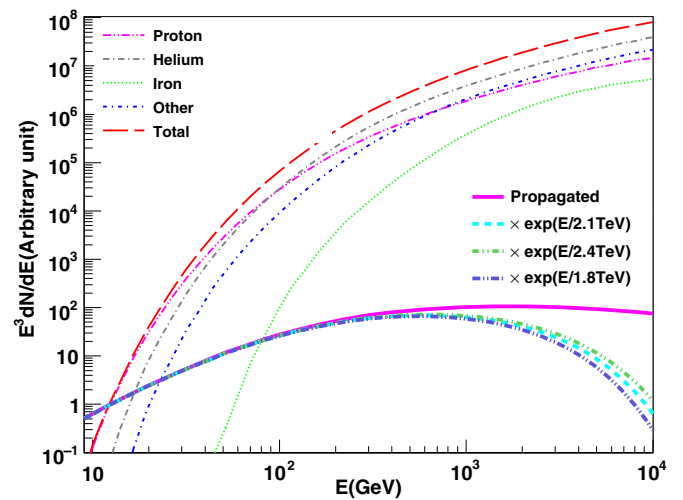


Figure 2. Upper-thin lines: electron/positron spectra generated through photon-nuclei interactions for various CR components. Lower-thick lines: propagated electron/positron spectra with arbitrary normalization. Also shown are the results with an exponential cutoff of the injection spectra with $E_c = 1.8, 2.1, 2.4$ TeV, respectively (Aharonian et al. 2008).

one simple set of the physical parameters of the CR sources seems to be sufficient to give good descriptions to the major

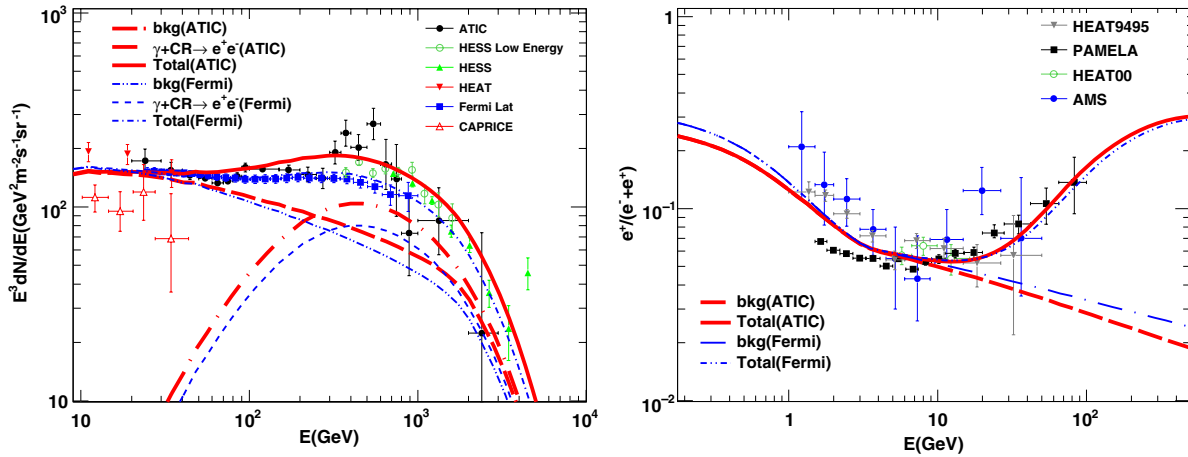


Figure 3. Left: total spectra for $e^+ + e^-$. The labels “ATIC” and “Fermi” in the brackets mean the results to fit ATIC or *Fermi* data, respectively. Observational data are: CAPRICE (Boezio et al. 2000), HEAT (Barwick et al. 1998), ATIC (Chang et al. 2008), H.E.S.S. (Aharonian et al. 2008), H.E.S.S. low energy (Aharonian et al. 2009), *Fermi*-LAT (Abdo et al. 2009). Right: positron fraction. Observational data are: AMS (Aguilar et al. 2007), HEAT94+95 (Barwick et al. 1997), HEAT00 (Coutu et al. 2001), PAMELA (Adriani et al. 2009).

properties of the data. It may indicate: (1) all the sources are “standard” and have similar parameters, (2) the average effect is equivalent to using single set of parameters, (3) one single nearby source dominates the observed fluxes of CRs, and so on. If the CRs indeed come from a single nearby source,⁴ one would expect a sharp knee of the CR spectra (Erykin & Wolfendale 1997). It is interesting to note that the Tibet AS γ experiment indeed observed a sharp knee structure (Amenomori et al. 2008a). Furthermore, the young SNR acceleration model predicts a sharp cutoff of electron spectra beyond several TeV which can be tested by future high quality experiments, such as the upgraded Tibet AS γ experiment with underground MUON detectors (Amenomori et al. 2008b), GRAPES,⁵ and KASCADE.⁶ Finally, we note that the current measurements of CR spectra around the knee energy are of great uncertainties for individual CR nuclei. If precise measurements become available in the future, it will be very helpful in understanding the model and in determining the model parameters.

We thank Li Tipei, Ding Linkai, Lü Caidian, Wang Jianxiong, Li Haibo, Liu Siming, Deng Jinsong, Lu Fangjun, Zhu Shouhua, Lou Yuqing, Olivier Martineau-Huynh, Artin Teymourian, and Wang Hanguo for helpful discussions. Hu Hong-Bo thanks Wang Wei for long-term help with the research work. This work is supported by the Minister of Science and Technology of China, Natural Sciences Foundation of China (Nos. 10725524 and 10773011), and by the Chinese Academy of Sciences (Nos. KJCX2-YW-N13 and KJCX3-SYW-N2). Fan Chao is partially supported by the Natural Science Foundation of Shandong Province, China (No. Q2006A02).

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⁴ Note that in such a case the background calculation of electrons/positrons using GALPROP might not be proper any more. However, phenomenologically we can adjust the source parameters to get similar spectra of electrons/positrons for a single source with the continuous source distribution, although there might be some constraints from, e.g., the diffuse gamma-rays. To build a fully self-consistent model of a single source scenario is beyond the scope of the present study.

⁵ <http://alpha.sci.osaka-cu.ac.jp/grapes3/index.html>

⁶ http://www-ik.fzk.de/KASCADE_home.html

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