On the Galactic Center being the main source of galactic cosmic rays as evidenced by recent cosmic ray and gamma ray observations

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New Journal of Physics 15 (2013) 013053 (9pp)
Received 19 September 2012
Published 22 January 2013
Online at http://www.njp.org/
doi:10.1088/1367-2630/15/1/013053

Abstract. We revisit the idea that the Galactic Center (GC) is the dominant source of galactic cosmic rays (GCRs), based on a series of new observational evidence. A unified model is proposed to explain the new phenomena of GCRs and γ-rays simultaneously. The GCRs are thought to be accelerated during past activities of the GC. The pair production process of GCRs in the strong radiation field due to the GC activity is responsible for the knee structure of the CR spectra. A fraction of e⁺e⁻ produced by pair production interactions can be reaccelerated in the induced bipolar jets and be transported into the halo, leaving the Fermi γ-ray bubbles and WMAP microwave haze as the remnant signal. Finally, the CRs diffuse in the bulge could further interact with the interstellar medium to produce low energy e⁺e⁻. After cooling down, these positrons may annihilate to produce the 511 keV line emission as discovered by INTEGRAL.

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1. Introduction

The origin of cosmic rays (CRs) has been a mystery since their discovery in 1912. CRs have a nearly featureless power-law spectrum with a spectral index of about $-3$ from energies of $\sim 10^9$ to $\sim 10^{20}$ eV. However, detailed measurements revealed several subtle structures in the CR spectrum at $\sim 4 \times 10^{15}$ eV (knee), $\sim 4 \times 10^{17}$ eV (second knee), $\sim 5 \times 10^{18}$ eV (ankle) and $\sim 6 \times 10^{19}$ eV (Greisen–Zatsepin–Kuzmin cutoff) [1]. The study of these structures is of great importance for understanding the origin, propagation and interaction of CRs.

It is generally believed that supernova remnants (SNRs) are the source of galactic CRs (GCRs), based on the simple argument that the power of supernovae is sufficient to sustain the total power of GCRs [2, 3]. But there are still some open questions for SNRs as the dominant source of GCRs, such as the isotopic abundance, radial gradient of CRs deduced from diffuse $\gamma$-rays and the maximum attainable energy of particles [4, 5]. The evidence from $\gamma$-ray observations is also indirect and inconclusive. Therefore, we had enough motivation to discuss the origin of GCRs beyond SNRs.

Instead of discussing the stellar level sources in the Galaxy, the Galactic Center (GC) as powered by accretion of the supermassive black hole could be a natural candidate for CR origin. Although the GC is relatively quiet nowadays, there is a large amount of evidence suggesting that the GC may have been active $\sim 10^7$ years ago [6–8]. Historically, there have been many discussions on the possibility that the GC is the dominant source of GCRs as a result of its activity [9–11].

There has been great progress in the measurement of GCRs and $\gamma$-rays in recent years. Firstly, owing to the improved energy resolution, a very sharp knee structure was found by many air shower array experiments [12–17]. This result seems to favor the single-source model as proposed in [18, 19]. Secondly, several high-precision measurements led to the discovery of both the positron fraction excess [20] and the total $e^+e^-$ spectral excess [21, 22] from $\mathcal{O}(10)$ GeV to TeV. It was also shown that the $e^+e^-$ spectra have a cutoff at several TeV [23, 24]. The result seems to also favor the single-source model proposed in [25]. Since the observational anisotropy of CRs is very weak ($10^{-4}$–$10^{-3}$), the single source should not be very close to us. The GC is one of the potential candidates [26]. Furthermore, the discoveries of the 511 keV line emission and $\gamma$-ray bubbles in the GC region indicate that the GC may indeed have past activities. Based on these new observational data, it is time to revisit the idea that the GC is the main source of GCRs.

In this work, we describe a unified model to explain the recent observations of CRs and $\gamma$-rays, based on the past activity of the GC.

New Journal of Physics 15 (2013) 013053 (http://www.njp.org/)
2. The model

During the active phase of the GC, the accretion of stars and gases by the supermassive black hole is very efficient in providing high enough power for particle acceleration, jet launch and propagation. The GC activities can produce shocks and accelerate CRs to high energies \([27, 28]\) in scales from \(\sim 10^{-3}\) pc \([29]\) to kpc \([30]\). The heating of the accretion disc fills it with thermal photons. Jets can also be produced due to the accretion events.

In the above-mentioned environment, the following physical processes are expected to occur. First we may have the primary acceleration of CRs around the black hole. The accelerated nuclei can then escape from the source region and enter the disc filled with background field. The interaction between CR nuclei and the background photons can lead to energy loss of CRs, which could result in the formation of the knee \([25]\). The interaction will produce \(e^+e^-\) pairs, which can be partially transported into the halo through the jets. Those electrons and positrons can then radiate to form the multi-wavelength haze/bubble. Finally, the CRs diffuse in the bulge could further interact with the interstellar medium to produce low energy \(e^+e^-\). After cooling down, these positrons may annihilate to produce the 511 keV line emission. The cartoon to describe the basic picture of the model is shown in figure 1. In the following, we will discuss more details of the three aspects, the origin of the knee, the multi-wavelength haze/bubble and the 511 keV emission, respectively.

2.1. Origin of the knee

Hu et al \([25]\) proposed a model to simultaneously explain the knee and the \(e^+e^-\) excess, incorporating pair production interactions between CRs and the ambient photon field. It was further shown that the irregular structures of the CR spectra around the knee region and the galactic ‘B component’ could also be well explained in this scenario \([31]\). As a consequence, one set of parameters in the mode of \([25]\) also favors the single-source model. It indicates that there might be a single source with relatively stable properties (during the CR acceleration period) that is responsible for GCRs.

In \([25]\), a supernova–pulsar system was proposed as a possible candidate for such a source. Although it is not impossible, it seems non-trivial for such a system to satisfy the conditions needed to produce the knee of the CRs \([32]\). Alternative candidate sources may include microquasars or the GC. The latter seems to be an especially attractive option \([26]\). As proposed by many studies, the capture of stars or accretion of gas by the central supermassive black hole can produce shock and accelerate particles \([27]\).

The density of background radiation field at the GC region is the key factor in determining whether the knee structure of CR spectra can be formed. As shown in \([25]\), the photon column density should be \(\sim 10^{30}\) cm\(^{-2}\)! Without firm observational evidence of the size of such a kind of interactions, we take 1 pc as an illustration. The infrared–optical photon density inside 1 pc of the GC was about \(10^4–10^5\) eV cm\(^{-3}\) in a flaring disc and dust \([33, 34]\). As an estimate, we adopt a value of \(5 \times 10^4\) eV cm\(^{-3}\). For photons with a typical energy \(\sim \text{eV}\), the photon number density is about \(5 \times 10^4\) cm\(^{-3}\). The diffusion velocity of CRs in the knee region is estimated to be of the order of \(10^{-3}\) of the light velocity, according to the measured anisotropy \([35]\). Therefore, the

\(^2\) Note that for such a photon field the photodisintegration and pion-production processes will be too strong. Since these two processes have higher threshold energy, they could be suppressed if the maximum energy of CRs does not exceed much beyond the knee.
Figure 1. A cartoon describing the unified model. The GCRs are accelerated in the most central region around the black hole, during past activities. Pair production processes of GCRs in the strong radiation field occur and are responsible for the knee structure of the spectra. A fraction of the produced $e^+e^-$ enters the halo and radiates to form the bubbles. The inelastic interactions between the CRs and the gas in the bulge and disc further produce the 511 keV line emission.

time for CRs to diffuse out of such a region is about $10^3$ years. So the photon column density that CRs can encounter is $n \tau \sim 10^{29} \text{ cm}^{-2}$, which is four orders of magnitude lower than that required. However, it is possible that the photon luminosity could be much higher during the active phase than at present. For example, the observation of infrared radiation from other galaxies showed that when the nucleus was in the active phase the infrared luminosity could be as high as $10^{44} - 10^{47} \text{ erg s}^{-1}$, which is two to five orders of magnitude higher than the present value of our Galaxy, $\sim 10^{42} \text{ erg s}^{-1}$ [9]. Therefore, it is possible that the background photon density could be four orders of magnitude higher during the active phase, and the condition to form the knee could be satisfied. Under these circumstances, the total energy of background photons is estimated to be $\sim 10^{53}$ erg, which is close to the accretion power of one solar mass.

2.2. Fermi bubbles: possible relics of past Galactic Center activity

If GC indeed plays a significant role in producing the GCRs, we may expect the existence of some relics of the past activity of GC. ‘Fermi bubbles’, the new observational evidence, may be such a kind of relics of the past GC activity.
Thanks to the high performance of a Fermi γ-ray telescope, a large-scale, extended γ-ray excess in the GC direction was discovered [36], which was then revealed to be two giant γ-ray bubbles [37]. The Fermi bubbles are symmetric with respect to the galactic plane, extending \( \sim 50^\circ \) in latitude and \( \sim 40^\circ \) in longitude. They are spatially correlated with the WMAP haze observed in the 20–60 GHz band [38, 39], and the edges of the bubbles are also found to be coincident with features in the ROSAT 1.5–2 keV x-ray maps [40]. Recently, the PLANCK collaboration confirmed the microwave haze found in WMAP data [41]. Several models were proposed to explain the Fermi bubbles [42–47], most of which are based on GC activity in the past.

The bubbles are found to have a hard γ-ray spectrum between 1 and 100 GeV, with a power-law index \( \sim -2 \). The γ-ray spectrum can be reproduced well by the inverse Compton scattering (ICS) process of power-law distributed electrons with index \(-2\) to \(-2.5\) [37], taking into account the cosmic microwave background, infrared and optical background radiation. In addition, the calculated synchrotron radiation can reproduce the radio haze flux, assuming that the magnetic field is of the order of 10 \( \mu \)G. However, this electron spectrum has difficulty in explaining the observed low energy drop below 1 GeV. In order to solve this problem, an electron population with a limited energy range was proposed. Based on these facts, Su et al [37] concluded that the bubbles are most likely created by a large episode of energy injection in the GC over the last \( 10^7 \) years through an accretion event in the center of the supermassive black hole, a nuclear starburst or some other energetic event.

The locally measured energy density of CRs is about 1 eV cm\(^{-3}\). Given that the volume of the galactic disc is about \( \pi(20 \text{ kpc})^2(0.2 \text{ kpc}) \sim 10^{67} \text{ cm}^3 \), the total energy of CRs is about \( 10^{55} \) erg. Assuming that the pre-propagated spectrum of GCRs is \( \propto E^{−2.0} \), the total energy of GCRs above the knee (\( E \sim \text{PeV} \)) is approximately \( 10^{54} \) erg. Such an energy will be mostly converted into \( e^+e^- \) through the pair production interactions. According to [37], the Fermi bubbles have an age of the order of \( 10^7 \) years. That is to say that the luminosity of \( e^+e^- \) is estimated to be \( 10^{39}−10^{40} \) erg s\(^{-1}\). The total luminosity of the Fermi bubbles in 1–100 GeV is estimated to be about \( 4 \times 10^{37} \) erg s\(^{-1}\) [37], which is much smaller than the above estimated value. That is to say, a small fraction of the produced \( e^+e^- \) could be enough to generate the Fermi bubbles\(^3\).

It should be noted that in the strong background radiation field, \( e^+e^- \) may cool down very efficiently. The timescale is estimated to be of the order of \( 10^{−2} \) year for TeV electrons. However, it is expected that there should also be acceleration in the jets and/or in the inner 1 pc region around the GC. The acceleration of the active galactic nuclei jet could be very efficient, such as minutes to hours [49], which may possibly compensate for the cooling of the \( e^+e^- \).

The \( e^+e^- \) spectrum used to calculate the synchrotron and ICS spectra is taken from [25], which can explain the \( e^+e^- \) excesses observed by PAMELA/ATIC/Fermi. For the interstellar radiation field (ISRF) model, we adopt that reported by Porter and Strong [50], in which a new calculation based on the modelings of star and dust distributions, the scattering, absorption and re-emission of the stellar light by dust was carried out. The ISRF model showed good agreement with the observational data [51], and was implemented in the public CR propagation code GALPROP [52]. Here we adopt the ISRF intensity at \( R = 0 \) and \( z = 4 \) kpc. The energy spectrum of the ISRF is shown in the left panel of figure 2. Three major components, optical from stars, far-infrared from dust and the cosmic microwave background, are clearly shown.

\(^3\) It can be seen below that the luminosity of the synchrotron emission is even higher than the γ-ray emission, which means that a higher fraction of the produced \( e^+e^- \) is necessary.
Figure 2. Left: the ISRF at \((R, z) = (0\, \text{kpc}, 4\, \text{kpc})\), taken from the GALPROP package. Right: the calculated spectrum of ICS \(\gamma\)-rays and synchrotron radiation originating from a reaccelerated electron spectrum generated through CR–photon pair production interactions. The line of sight direction is chosen to be \(l = 0^\circ\) and \(b = 25^\circ\). The data points representing the Fermi bubbles and WMAP haze are taken from table 3 and figure 23 of [37].

The right panel of figure 2 shows the resulting synchrotron and ICS spectra by the e\(^+\)e\(^-\). The magnetic field is assumed to be \(B = 15\, \mu\text{G}\), and the Klein–Nishina cross section of ICS is adopted. The spectra of WMAP synchrotron haze and Fermi ICS bubbles are consistently generated.

2.3. The 511 keV line emission

It is natural to expect a possible connection of the GC origin of CRs with the 511 keV line emission as reported by several experiments [53–56], although the most popular model of 511 keV emission is the decay of radioactive isotope [57]. The 511 keV line emission indicates the existence of non-relativistic positrons in the GC region. The hadronic interactions of GCRs with the ambient gas could be one potential source of these positrons [27, 58, 59]. We make an order of magnitude estimate of the power of electrons. The total number of CR protons is about \(\sim 10^{58}\), for a local number density of \(\sim 10^{-9}\, \text{cm}^{-3}\) and the volume of the Galactic disc of \(\sim 10^{67}\, \text{cm}^3\). Considering that the size of the Galactic bulge is \(\sim 1\, \text{kpc}\), the typical path length that a particle travels from the GC to outside of the bulge should be \(\sim 10^3\, \text{kpc}\), for diffusion coefficient \(D \sim 5 \times 10^{28}\, \text{cm}^2\, \text{s}^{-1}\). Assuming that the number density of ISM nuclei in the bulge is \(1\, \text{cm}^{-3}\) and the inelastic cross section of \(p–p\) scattering is several tens of mb, the average number of collisions for one CR proton before traveling out of the bulge is \(\sim 0.1\). Thus, the total number of positrons is \(\sim 10^{57}\). Assuming that the cooling time of positrons is about \(10^7\, \text{years}\), which corresponds to the ionization and Coulomb losses in an ISM with a density of \(1\, \text{cm}^{-3}\) for a \(100\, \text{MeV}\) positron [52], the cooled positron production rate is \(3 \times 10^{42}\, \text{s}^{-1}\), which is comparable with the rate \(10^{43}\, \text{s}^{-1}\) as implied by the flux of the 511 keV \(\gamma\)-ray line [54].

However, it was pointed out that the diffuse \(\gamma\)-ray constrained positron production rate would not be more than a few per cent of the positron rate suggested by the 511 keV emission data [27, 54, 60]. This problem can be solved in a non-stationary scenario that the GC was
in active phases in the past and the positron production rate would be much higher than that determined by the current diffuse $\gamma$-ray flux [27, 60].

3. Conclusion and discussion

In this paper, we propose that the GC is a major source of GCRs. There is evidence to show the past activity of the GC. Particle acceleration can take place during the violent phase of the GC. Also, the existence of a strong radiation field around the GC is expected. Thus, efficient $e^+e^-$ pair production interactions between GCRs and the ambient photons might be responsible for the knee of the CR spectra [25]. A fraction of $e^+e^-$ produced by pair production interactions can be reaccelerated in the jets and escape into the halo. The ICS and synchrotron radiation of these $e^+e^-$ may possibly explain the observed Fermi bubbles and WMAP haze.

Even though the jet can transport the $e^+e^-$ very efficiently into the halo, the propagation of these particles from the jet to the whole bubble is still an open question. If we adopt the diffusion velocity of $10^{-3} \, c$ as in the disc, the electrons/positrons need $10^7$ years to travel $\sim 5$ kpc. It is much larger than the typical cooling time ($< 10^6$ years [37]) of TeV electrons. However, a faster transportation of the particles in the halo is possible.

Because of the lack of knowledge about the Galaxy magnetic field, the phenomenological model is generally used to study the propagation of GCRs in the Galaxy. As we know, the halo is much larger than the disc. But the average density of the medium GCRs travel is $\sim 0.3$ cm$^{-3}$, while the disc density is about 1 cm$^{-3}$ [61]. So the trapping time of GCRs in the halo is only about two times longer than in the disc. We can infer that the propagation velocity in the halo is much faster than in the disc. It is possible to conclude that the stochastic magnetic field is much smaller in the halo than in the disc. We need to investigate particle transportation in the regular halo magnetic field [62] to study propagation of particles in the halo, instead of the uniform diffusion in the Galaxy. Therefore, the $e^+e^-$ may fill in the whole bubble within the cooling time through the fast propagation. However, the detailed model is beyond the scope of the present work.

The anisotropy of GCRs may still be an open question in the GC scenario of the origin of GCRs. Still the different propagation patterns in the disc and the halo may lead to different results on the expected anisotropy. We leave the discussion of it to future work.

Finally, we should note that in the jet the background electrons should also be accelerated together with the $e^+e^-$ produced through CR–photon interactions. In such a case, the total electron spectrum used to calculate the bubble/haze emission might be different from what is adopted in this work. Without loss of generality, we may expect the background electron spectrum to be a power-law spectrum $\sim E^{-2}$ with a cutoff which does not differ much from that we use here. The basic results in this work should not change significantly.

Acknowledgments

We thank Shaoxia Chen for helpful discussion and Yigang Xie, Amanda Maxham, Ann Meng Zhou and Hanguo Wang for useful comments on the paper. This work was supported by the Ministry of Science and Technology of China, the Natural Sciences Foundation of China (grant numbers 10725524, 10773011 and 11135010) and the Chinese Academy of Sciences (grant numbers KJCX2-YW-N13, KJCX3-SYW-N2 and GJHZ1004).
References

[1] Hörandel J R 2007 Mod. Phys. Lett. A 22 1533
[2] Baade W and Zwicky F 1934 Phys. Rev. 46 76
[3] Ginzburg V L and Syrovatskii S I 1964 The Origin of Cosmic Rays (New York: Macmillan)
[4] Hillas A M 2005 J. Phys. G: Nucl. Part. Phys. 31 95
[5] Butt Y 2009 Nature 4 60 701
[6] van der Kluit P C 1971 Astron. Astrophys. 13 405
[7] Sanders R H and Prendergast K H 1974 Astrophys. J. 188 489
[8] Erlykin A D and Wolfendale A W 2007 J. Phys. G: Nucl. Part. Phys. 34 1813
[9] Ptuskin V S and Khazan Y M 1981 Astron. Zh. 58 959
[10] Said S S, Wolfendale A W, Giler M and Wdowczyk J 1981 Proc. 17th Int. Cosmic Ray Conf. (Paris) vol 2 p 344
[11] Giler M 1983 J. Phys. G: Nucl. Phys. 9 1139
[12] Chilingarian A et al 2007 Astropart. Phys. 28 58
[13] Korosteleva E E, Prosin V V, Kuzminiev L A and Navarra G 2007 Nucl. Phys. B 165 74
[14] Garyaka A P et al 2008 J. Phys. G: Nucl. Part. Phys. 35 115201
[15] Amenomori M et al 2008 Astrophys. J. 678 1165
[16] Apel W D et al 2009 Astropart. Phys. 31 86
[17] Ivanov A A, Knurenko S P and Sleptsov I Y 2009 New J. Phys. 11 065008
[18] Erlykin A D and Wolfendale A W 1997 J. Phys. G: Nucl. Part. Phys. 23 979
[19] Erlykin A D and Wolfendale A W 2009 arXiv:0906.3949
[20] Adriani O et al 2009 Nature 458 607
[21] Chang J et al 2008 Nature 456 362
[22] Abdo A A et al 2009 Phys. Rev. Lett. 102 181101
[23] Aharonian F et al 2008 Phys. Rev. Lett. 101 261104
[24] Aharonian F et al 2009 Astron. Astrophys. 508 561
[25] Hu H-B et al 2009 Astrophys. J. 700 L170
[26] Hu H 2009 Proc. 31st Int. Cosmic Ray Conf. (Lódź 2009) pp 87–94 (arXiv:0911.3034)
[27] Cheng K S et al 2006 Astrophys. J. 645 1138
[28] Bell A R and Lucek S G 2001 Mon. Not. R. Astron. Soc. 314 65
[29] Albert J et al 2008 Astrophys. J. Lett. 685 L23
[30] Su M et al 2012 Astrophys. J. 753 61
[31] Wang B et al 2010 Sci. China G 53 842
[32] Erlykin A D, Wibig T and Wolfendale A W 2011 Astrophys. Space Sci. Trans. 7 179
[33] Davidson J A et al 1992 Astrophys. J. 387 189
[34] Mezger P G, Duschl W J and Zylka R 1996 Astron. Astrophys. 7 289
[35] Aglietta M et al 2003 Proc. 28th Int. Cosmic Ray Conf. p 183
[36] Dobler G, Finkbeiner D P, Cholis I, Slatyer T and Weiner N 2010 Astrophys. J. 717 825
[37] Su M, Slatyer T R and Finkbeiner D P 2010 Astrophys. J. 724 1044
[38] Finkbeiner D P 2004 Astrophys. J. 614 186
[39] Dobler G and Finkbeiner D P 2008 Astrophys. J. 680 1222
[40] Snowden S L et al 1997 Astrophys. J. 485 125
[41] Ade P A R 2012 arXiv:1208.5483v1
[42] Guo F et al 2012 Astrophys. J. 756 182
[43] Cheng K S et al 2011 Astrophys. J. 731 L17
[44] Crocker R M and Aharonian F 2011 Phys. Rev. Lett. 106 101102
[45] Guo F and Mathews W G 2011 arXiv:1103.0055
[46] Istomin Y N 2011 arXiv:1110.5436

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[47] Mertsch P and Sarkar S 2011 Phys. Rev. Lett. 107 091101
[48] Zubovas K, King A R and Nayakshin S 2011 Mon. Not. R. Astron. Soc. 415 21
[49] Aharonian F et al 2007 Astrophys. J. Lett. 664 L71
[50] Porter T A and Strong A W et al 2005 Proc. 29th Int. Cosmic Ray Conf. 4 77
[51] Moskalenko I V, Porter T A and Strong A W 2006 Astrophys. J. 640 L155
[52] Strong A W and Moskalenko I V 1998 Astrophys. J. 509 212
[53] Johnson W N et al 1972 Astrophys. J. 172 L1
[54] Knödlseder J et al 2005 Astron. Astrophys. 441 513
[55] Jean P et al 2005 Astron. Astrophys. 445 579
[56] Weidenspointner G et al 2008 Nature 451 159
[57] Prantzos N et al 2011 Rev. Mod. Phys. 83 1001
[58] Ramaty R et al 1970 J. Geophys. Res. 75 1141
[59] Totani T 2006 Publ. Astron. Soc. Japan 58 965
[60] Porter T et al 2008 Astrophys. J. 682 400
[61] Maurin D et al 2001 Astrophys. J. 555 585
[62] Beck R 2001 Space Sci. Rev. 99 243