On the Galactic Center Being the Main Source of Galactic Cosmic Rays as Evidenced by Recent Cosmic Ray and Gamma Ray Observations

Yiqing Guo, Zhaoyang Feng, Qiang Yuan, Cheng Liu, Hongbo Hu
Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Science, Beijing 100049, P.R. China

Abstract: We revisit the idea that the Galactic center is the dominant source of Galactic cosmic rays, based on a series of new observational evidence. Possible evidence supporting such an idea includes: the sharp knee of the cosmic ray spectrum around PeV energies, the giant γ-ray bubbles revealed by Fermi data, the microwave haze observed by WMAP, and the 511 keV line emission discovered by INTEGRAL.

Keywords: cosmic rays, Galaxy, Galactic center, Fermi Bubibbles, 511keV line emission

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 $\sim 10^{20}$ to $\sim 10^{20}$ eV. However, detailed measurements revealed several subtle structures in the CR spectrum [1] at $\sim 10^{15.5}$ eV (the knee), $\sim 10^{17.8}$ eV (the second knee), $\sim 10^{19}$ eV (the ankle), and $\sim 6 \times 10^{19}$ eV (GZK cut-off). The study of these structures is of great importance for understanding the origin and interaction of CRs.

Although there are hundreds of GeV γ-ray sources [2] and several tens of TeV γ-ray sources [1] being detected in the Galaxy, direct evidence of the origin of Galactic CRs (GCRs) is still lacking. It is generally believed that CRs below the knee are accelerated in shock waves of supernova remnants (SNRs) within the Galaxy. The total power needed to sustain CRs is estimated to be $\sim 10^{40}$ erg/s, assuming an energy density of CRs $\sim 1$ eV cm$^{-3}$, the height of CR confinement $\sim 0.2$ kpc and the age of CRs $\sim 10^8$ yr [3]. This power is consistent with the power released by Galactic supernova explosions.

However, there are also many arguments against the idea that SNRs are responsible for GCRs [4, 5]. First, the maximum energy of CRs from SNR acceleration typically can not exceed $10^{14}$ eV, whereas the Galactic component of CRs is expected to extend out to above $10^{17}$ eV. Second, the accelerated CRs are expected to interact with the ambient medium to produce neutral pions, which would further decay into high energy γ-rays. However, many observations show that the γ-ray flux from SNRs are much lower than that predicted. Third, according to the model, high energy CRs are expected to escape quickly from our Galaxy after a short trapping time converting the $E^{-2}$ injection spectrum to the observed $E^{-2.7}$ spectrum. Such a fast escape should result in a large anisotropy (e.g., $5\%$ at 100 TeV) of GCRs, which contradicts the observed data (only $\sim 0.03\%$, [6, 7]).

There has been great improvement in the measurement of GCRs in recent years. First, owing to the improved energy resolution, a very sharp knee structure was found by many Air Shower array experiments, such as MAKET-ANI [8], Tunka [9], GAMMA [10] and Yakutsk [13]. This result seems to favor the single source model proposed in Erlykin & Wolfendale[1997][14] and Erlykin & Wolfendale(2009)[15], although this model predicts a larger anisotropy of CRs than that observed.

Second, several high precision measurements led to the discovery of both the positron fraction excess [16] and the total $e^+e^-$ spectral excess [17, 18] between $O(10)$ GeV and TeV. It was also shown that the $e^+e^-$ spectra have a cutoff at several TeV [19, 20].

Hu et al.[21] 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 [22]. As a consequence, one set of parameters in the model of Hu et al.[21] 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 Hu et al.[21] a supernova-pulsar system was proposed as a possible candidate for such a source. Though it is not yet confirmed by observations, this scenario may be worth further investigation. However, there are also arguments against this idea [23]. For example, the maximum energy of CRs from SNR acceleration typically can not exceed $10^{14}$ eV, whereas the Galactic component of CRs is expected to extend out to above $10^{17}$ eV. Second, the accelerated CRs are expected to interact with the ambient medium to produce neutral pions, which would further decay into high energy γ-rays. However, many observations show that the γ-ray flux from SNRs are much lower than that predicted. Third, according to the model, high energy CRs are expected to escape quickly from our Galaxy after a short trapping time converting the $E^{-2}$ injection spectrum to the observed $E^{-2.7}$ spectrum. Such a fast escape should result in a large anisotropy (e.g., $5\%$ at 100 TeV) of GCRs, which contradicts the observed data (only $\sim 0.03\%$, [6, 7]).
impossible, it seems non-trivial for such a system to satisfy the conditions needed to produce the knee of the CRs [23]. Alternative candidate sources may include micro-quasars or the Galactic center (GC). The latter seems to be an especially attractive option [24]. 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 [25].

Based on the interstellar radiation field model in GALPROP [26, 27], the optical photon density ($\sim$eV) in the GC is about $10^{26}$ cm$^{-2}$, which corresponds to a photon column density $\nu e$/$\tau$ $\sim$ $10^{26}$ cm$^{-2}$ for an assumed interaction time of $10^{7}$ yr. This value is about 4 orders of magnitude lower than that required in Hu et al.[21]. However, if the GC was in active phase in the past, the photon fields would be several orders of magnitude higher than the present value. 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 $10^{34}$ - $10^{47}$ erg/s, which is $2 - 5$ orders of magnitude higher than the present result of our Galaxy $\sim$ $10^{42}$ erg/s [28]. So it is possible that the GC is responsible for the interaction to make the knee of CRs.

Historically, there have been many discussions on the possibility that the GC is the dominant source of GCRs. There is a large amount of evidence suggesting that the GC may have been active $\sim$ $10^{7}$ years ago (van der Kruit 1971[29], Sanders & Prendergast 1974[30], Erlykin & Wolfendale 2007[31], see section 6.1 of Su et al.[32] for a detailed summary). Based on the evidence that an explosion occurred about $10^{7}$ years ago in the GC, [28] proposed a "central-source model" of CRs, in which the bulk of GCRs are accelerated in the GC during its active phases, and the active phases reoccur every $10^{7} - 10^{8}$ years. The similar idea was examined by other authors [33, 34].

Within the framework of the new observations, it is time to revisit the idea that the GC is the main source of the bulk of GCRs. In this work we will investigate the compatibility of the GC origin scenario of GCRs with the recent observations.

2 Analysis

According to the model of Hu et al.[21], TeV electrons and positrons are produced when CRs are accelerated at the source. As electrons and positrons can travel a much shorter distance than that of heavier CR nuclei, the majority of these electrons and positions should remain in the source region (e.g., the GC here). These electrons and positrons in the source region can produce radio, X-ray and GeV $\gamma$-ray photons through the processes of synchrotron radiation and Inverse-Compton (IC) scattering. When diffusing out of the source region, the GCRs will interact with interstellar matter, producing a large amount of GeV electrons and positrons. Positrons can then cool down and annihilate with interstellar electrons to produce 511 keV line emission. In short, if the GCRs indeed come from GC and the mechanism proposed by Hu et al.[21] works, the GC region should have powerful multi-wavelength radiation. This is exactly what has been recently observed.

By analyzing the Fermi-LAT data, Dobler et al.[35] first discovered extended excess emission in the GC region, or the so-called "Fermi haze". With even more data, Su et al.[32] revealed that there were actually two giant $\gamma$-ray bubbles (Fermi bubbles), which are symmetric with respect to the Galactic plane, extending $\sim$ 50 degrees in latitude and $\sim$ 40 degrees in longitude. The bubbles are spatially correlated with the WMAP haze observed in the 20 – 60 GHz band [36, 37]. The edges of the bubbles are also found to be coincident with features in the ROSAT 1.5 – 2 keV X-ray maps [38]. These correlations indicate that the bubbles very likely originated from the electron process described above.

The bubbles are found to have a hard $\gamma$-ray spectrum between 1 and 100 GeV, with a power law index $\sim$ $-2$.

The $\gamma$-ray spectrum can be well reproduced by the IC scattering process of power-law distributed electrons with index $-2 \sim 2.5$ [32], 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 explaining the observed low energy drop below 1 GeV. In order to solve this problem, an electron population with limited energy range was proposed. Based on these facts, [32] concluded that the bubbles are most likely created by a large episode of energy injection in the GC in the last $10^{7}$ years through an accretion event in the center of supermassive black hole, a nuclear starburst or some other energetic event. Alternatively, [39] employed the hadronic mechanism to reproduce the observed spectra.

In this work we propose that the $e^+e^-$ spectra is produced by pair production through CR-photon interaction (the mechanism suggested in Hu et al.[21]), and that this mechanism can give a good fit to the data. The injected electron spectrum used in this calculation includes propagation effects as well as the cut-off effect at about 2 TeV, i.e., the same spectrum used to explain the ATIC-like $e^+e^-$ excesses. The background radiation field is adopted from GALPROP version 50p5 with $R = 0$ and $z = 4$ kpc. The calculated synchrotron and IC spectra for such a population of electrons are shown in Fig.1. Here we assume the magnetic field is $B = 25 \mu$G. The results are in good agreement with the data.

The total luminosity of the Fermi bubbles in 1 – 100 GeV is estimated to be about $4 \times 10^{37}$ erg/s. If we assume the power of all GCRs is about $10^{49}$ erg/s, then the power of CRs above the knee ($E \sim 4$ PeV) is approximately $10^{39} - 10^{48}$ erg/s with the source spectrum $E^{-2.0} \sim E^{-2.2}$.

Note for the $E^{-2.0}$ spectrum we assume the maximum achievable energy of CRs is $10^{9}$ GeV. Assuming that the main fraction of the GCR power above the knee converts to $e^+e^-$ and the fast cooling of $e^+e^-$ will soon convert most

---

\[ \text{http://galprop.stanford.edu/} \]
Figure 1: The calculated spectrum of IC scattering γ-rays and synchrotron radiation originating from a hard electron spectrum generated through CR-photon pair production interactions. The line of sight direction is chosen to be \( \ell = 0^\circ \) and \( b = 25^\circ \). The data points representing the Fermi bubbles and WMAP haze are taken from Table 3 and Fig. 23 of [32]. The spectra of WMAP synchrotron haze and Fermi IC bubbles are consistently generated.

of their energy to photons, this gives a luminosity consistent with the observed Fermi bubbles. We may then speculate that the GC produced the bulk of the GCRs, and the interaction of the GCRs with an ambient photon field could explain the knee of the GCRs spectra, the Fermi bubbles and the WMAP haze around the GC.

Finally we investigate the possible connection of the GC origin of GCRs with the 511 keV line emission. The measurements of the 511 keV line emission in the GC has a long history [40]. Recently, very precise morphology and spectral properties of this emission were revealed by the SPI instrument onboard the INTEGRAL satellite [41, 42, 43]. The 511 keV line emission indicates the existence of non-relativistic positrons in the GC region. There are extensive discussions on the possible origins of the positrons, including the \( \beta^+ \) decay of radioactive isotopes [44], \( e^+e^- \) pair production from pulsars [45] and X-ray binaries [46], and exotic sources such as dark matter annihilation [47]. It is also possible that the positrons originated from the decay of \( \pi^+ \) produced in inelastic collisions between CRs and the interstellar medium (ISM) [48, 25, 49]. Past activity of the supermassive black hole in the GC could produce large amounts of CR nuclei which may interact with the ISM and produce positrons. After thermalization, these positrons can generate the observed 511 keV line flux.

This mechanism can also work in our scenario. The CRs (nuclei) accelerated in the GC will diffuse out of the Galactic bulge, and produce positrons during the propagation process. Heavy CRs can travel much longer than positrons, allowing them to eventually reach the Earth and be recorded by a detector. Due to the fast energy loss of positrons through ionization, Coulomb collisions, bremsstrahlung radiation, synchrotron radiation and IC scattering, positrons will cool down quickly and be trapped in the Galactic bulge. Eventually, when these positrons become non-relativistic, they can annihilate with the ambient electrons to form positronium and then emit 511 keV γ-rays.

An order of magnitude estimate of the power supports this idea. The locally measured number density of CRs is about \( 10^{-19} \) cm\(^{-3}\). The total number of GCRs should be on the order of \( 10^{58} \), giving that the volume of the Galactic disk is \( \pi (20 \text{kpc})^2 (0.2 \text{kpc}) \sim 10^{67} \text{cm}^3 \). Considering that the size of the Galactic bulge is \( 1 \) kpc, the typical path length that a particle travels from the GC to outside of the bulge should be \( 10^3 - 10^4 \) kpc, as the diffusion coefficient \( D \sim 10^{28} \text{cm}^2 \text{s}^{-1} \). Moreover, considering that the number density of ISM nuclei in the bulge is \( 1 \) cm\(^{-3}\), and the inelastic cross section of \( p-p \) scattering is several tens of mb, the average number of collisions for one CR particle before traveling out of the bulge is \( 0.1 - 1 \). Thus, the total number of positrons is \( 10^{57} - 10^{58} \). Assuming the cooling time of positrons is about \( 10^7 \) years, which corresponds to the ionization and Coulomb losses in an ISM with density of \( 1 \) cm\(^{-3}\) for a 100 MeV positron [26], the cooled positron production rate is \( 10^{43} - 10^{44} \text{s}^{-1} \), which is the rate required by the flux of 511 keV γ-ray line [41].

However, it was pointed out that the diffuse γ-ray constrained positron production rate would be not more than a few percent of the positron rate suggested by the 511 keV emission data [41, 25, 50]. 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 γ-ray flux [25, 50].

3 Summary

In summary, we propose that the GC is the main source of GCRs. The acceleration of these GCRs could take place during a past violent phase of the GC. By introducing an efficient \( e^+e^- \) pair production mechanism through the interaction between GCRs and ambient photons, we can explain the knee of the CR spectra. The produced \( e^+e^- \) have a low energy cut-off due to the threshold effect of pair production, which can naturally reproduce the recently discovered Fermi bubbles and WMAP haze. Furthermore, the production of positrons due to inelastic collisions of CRs and the ISM may explain the strong 511 keV line emission in the GC region.

4 Acknowledgments

We thank Yigang Xie, Amanda Maxham, Ann Meng Zhou and Hanguo Wang for very useful comments on the writing of this paper. This work is supported by the Ministry of Science and Technology of China, Natural Sciences Foundation of China (Nos. 10725524 and 10773011), and the Chinese Academy of Sciences (Nos. KJCX2-YW-N13, KJCX3-SYW-N2, GJHZ1004).
References

[1] Nagano, M., & Watson, A. A., Reviews of Modern Physics, 2000, 72, 689
[23] van der Kruit, P. C., AAP, 1971, 13, 405
[40] Guessoum, N. et al., AAP, 2006, 457, 753
[41] Boehm, C. et al., PRL, 2004, 92, 101301