Unified description of the GeV-TeV gamma ray spectra of supernova remnants

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Abstract: More and more supernova remnants have been revealed to be high energy γ-ray emitters thanks to the spatial telescope Fermi-LAT and ground-based very high energy γ-ray detectors. The GeV-TeV γ-ray spectra of the SNRs show very diverse properties. By means of the environmental medium density parameter only, we can uniformly account for the distinct behaviors of the γ-ray spectra of the SNRs. For low density environments, the γ-ray emission is inverse-Compton dominated and the energy spectrum is in general very hard. For high density environments like systems of high-energy particles interacting with molecular clouds, the γ-ray emission is π^0-decay dominated and the spectrum is soft. The inferred electron-to-proton ratio at the acceleration sites of SNRs is about 1%, which is also close to the value of locally observed cosmic rays. These results can be regarded as evidence in support of the SNR-origin of the Galactic cosmic rays.

Keywords: gamma-rays, cosmic rays, supernova remnants

1 Introduction

The origin of the cosmic rays (CRs) remains unknown after 100 years of the discovery. The supernova remnants (SNRs) are widely believed to be the candidate sources of the CRs, at least for those with energies below the "knee" [1, 2, 3]. The multi-wavelength observations of SNRs, especially the (very) high energy γ-rays, do support the efficient particle acceleration in vicinity of SNRs [4, 5, 6, 7, 8]. However, whether the nature of these γ-ray emission from SNRs is predominantly hadronic or leptonic is still a matter of debate. That is to say, SNRs are known particle accelerators, but it is not clear whether they accelerate efficiently the hadronic CRs and whether they dominate the observed Galactic CR flux on the Earth.

Thanks to the development of γ-ray detection by the imaging atmospheric Cerenkov telescopes (IACTs) such as H.E.S.S., MAGIC and VERITAS, and the spatial telescope Fermi-LAT, more and more SNRs have been viewed in this (very) high energy domain. It enables us to study more extensively the SNRs, as a population of particle accelerators. However, the observational γ-ray spectra of SNRs show significant diversity. Recent Fermi observations of the young SNR RX J1713.7-3946 shows a very hard spectrum in GeV energy range, 1.50 ± 0.11, which implies an inverse-Compton origin of the γ-rays [9]. On the other hand, for all of the SNRs interacting with molecular clouds (MCs), the GeV-TeV γ-ray spectra are generally very soft and seem to better agree with the π^0-decay model, although the model of bremsstrahlung emission from electrons can not be ruled out [10, 11, 12, 13, 14, 15, 16, 17]. It is natural to ask whether there is a common understanding of these γ-ray signatures of the SNRs.

There are many factors to affect the γ-ray spectra from one SNR, such as the age [18] or progenitor. In [19] we propose that the diversity of the γ-ray spectra could be due simply to the environmental medium density of the SNRs. According to the ambient medium density the SNRs are classified into three classes. For the sources located in low density environment, the γ-ray emission is dominated by the inverse Compton scattering (ICS) of the electrons off the interstellar radiation field (ISRF), which results in a hard GeV-TeV spectrum. For those interacting with molecular clouds the γ-ray emission is dominated by the π^0 decay from hadronic pp collision and the spectrum is generally very soft. The intermediate case have a combined origin of the ICS component and the π^0 decay component. The diversity of the γ-ray spectra of SNRs can be well understood in such a simple scenario. Furthermore, the inferred electron-to-proton ratio, K_{ep}, at the sources is close to the locally observed value at the Earth with proper propagation corrected, which could be an evidence to support the SNR-origin of the observed CRs.

2 Determining K_{ep} at the source

The electron-to-proton ratio at the acceleration sources, K_{ep}, is usually assumed to be a free parameter when modeling the multi-wavelength emission. However, we have local measurements of both the electrons and protons, for example by the satellite detector PAMELA [20, 21], as shown in Fig. 1. The charged particles will experience complicated propagation in the Milky Way after the production, and we know that the propagation effects of electrons are different from that of protons [22]. Nevertheless we can infer the source spectra of the electrons and protons after proper consideration of the propagation effect.

We adopt the GALPROP package [23], which is shown to be able to reproduce most of the observational results of the CRs including the isotope ratios and individual spectra as well as the diffuse γ-ray emission [24], to calculate the propagation of CRs. The injection spectral shape of both the electrons and protons is assumed to be a broken power-law function with respect to the momentum p

$$q(p) \propto \begin{cases} p^{-\alpha_1}, & p < p_{\rm br}, \\ p^{-\alpha_2}, & p \geq p_{\rm br}. \end{cases} \quad (1)$$

The parameters are taken to be identical for both electrons and protons. The only difference between electrons and

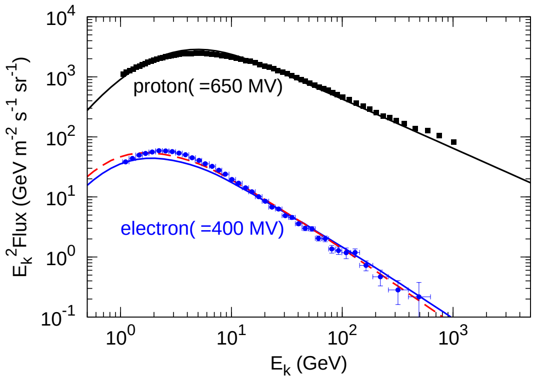

Fig. 1: The propagated fluxes of CR protons (upper) and electrons (lower) at the Earth, for the same spectral shape of the injected particles, compared with the PAMELA observational data [20, 21]. We adopt two parameter settings to calculate the electron spectrum: for solid line the magnetic field is the canonical one adopted in GALPROP and $K_{ep} \approx 1.3\%$; for dashed line the magnetic field is two times larger and $K_{ep} \approx 1.9\%$.

protons are the ratio of the normalizations, i.e., K_{ep}. We adopt the diffusion reacceleration regime of the propagation, and the main propagation parameters are $D_0 = 6.59 \times 10^{28}$ cm^{2}s^{-1}, $\delta = 0.30$, $v_A = 39.2$ km s^{-1} and $z_h = 3.9$ kpc, which are derived through the fit to the B/C, ^{10}Be/^{9}Be, Carbon and Oxygen data [25].

We find that adopting $\alpha_1 = 1.80$, $\alpha_2 = 2.52$ and $p_{\rm br} = 6$ GeV can give an acceptable fit to both the proton and electron data, as shown by the solid lines in Fig. 1. Note the low energy fluxes will be modulated by the solar activity, and we simply adopt the force-field approximation to acount for its effect [26]. Of course it is not the best-fit to the data. The electron spectrum seems to be too hard compared with the data. It might be due to the uncertainties of the treatment of the propagation. As an illustration we increase the magnetic field by a factor of two, which will result in larger energy loss of electrons during the propagation. The result (dashed line) fits better with the data. On the other hand, the accelerated spectra of electrons and protons may also differ even at the source due to, for example, the energy loss of electrons during the acceleration. Here we just use the fewest number of parameters to get the rough parameters of the source spectra.

The value of K_{ep} derived through fitting to the observed CR fluxes is about 1.3% (or 1.9% for the case with two times larger magnetic field). Such a value equals almost the measured ratio between electrons and protons around GeV, where the energy loss of electrons is not important and the propagation effects between these two species are similar.

3 Gamma-ray spectra of SNRs

With the spectral parameters and K_{ep} value derived from the locally observed CR fluxes, we study the γ-ray emission from SNRs. The γ-rays are generally produced by three processes: the π^0 decay through hadronic pp collisions, the ICS between electrons and ISRF, and the bremsstrahlung radiation of electrons in the interstellar medium (ISM). To calculate the γ-ray spectrum of individual source, we need further to know the environment parameters such as the ISM density and the ISRF. We employ the cosmic microwave background as the background radiation field in this study. The infrared and optical components of the ISRF differ place by place in the Milky Way, and is not expected to affect the qualitative result[1] in this work. Therefore the only free parameter to determine the γ-ray spectral shape is the ISM density[2].

The γ-ray SNRs can then be classified into three classes: the low density ones, mediate density ones and high density ones. For the shell-type SNRs RX J1713.7-3946 and RX J0852.0-4622, the lack of thermal X-ray emission place very stringent upper limits on the gas density to be the order of 0.01 cm^{-3} [27, 28, 29]. The expected γ-ray spectra of these two sources are shown in Fig. 2. We can see that in this case the π^0 decay and bremsstrahlung components are significantly suppressed sue to the low ISM density. The GeV-TeV γ-ray emission is dominated by the ICS component, and the spectrum is very hard. To be consistent with the high-energy spectral cutoff behavior of both SNRs, we employ an exponential cutoff term with $E_c \approx 60$ TeV of the electron spectra. The cutoff might be due to the balance of acceleration and the cooling in the vicinity of the SNR. No cutoff of protons is assumed here.

Another class is the systems of SNR interacting with molecular clouds. The target gas density is very high in this case, e.g., $10^2 - 10^3$ cm^{-3}. As an illustration we adopt $n = 100$ cm^{-3} in this study. Fig. 3 shows the comparison of the expected γ-ray spectra and the observational data for W51C and IC 443. For a larger sample of such souces please see Ref. [19]. In this case the GeV-TeV γ-ray emission is π^0-decay dominated, and the γ-ray spectrum is generally very soft.

There are intermediate cases with a moderate gas density, $\sim$cm^{-3}, which is the typical average value of ISM. We classify Cassiopeia A and Tycho as examples of this intermediate class. The average gas density of Cassiopeia A is estimated to be about 4.4 cm^{-3} [41]. For Tycho an upper limit $n < 0.6$ cm^{-3} was derived from the absence of thermal X-ray emission from the bright outer rim of the remnant [42]. The density in the inner region of the remnant can be much higher. The expected γ-ray spectra of these two sources are shown in Fig. 4, assuming $n = 1$ cm^{-3}. For this kind of sources the GeV emission is π^0-decay dominated and the TeV emission is ICS dominated. The luminosities in GeV and TeV bands are comparable in this case. We should note that the observational data still have large errors and the estimate of the gas density is also very uncertain. It is not absolutely necessary to intriduce two components to reproduce the γ-ray data of these two sources.

Finally we give the scattering plot of the photon index Γ and the ISM density n in Fig. 5. The Γ index is derived through fitting to the 1 GeV to 1 TeV γ-ray data. For the molecular clouds the gas density is not well measured we assume a value of $10^2 - 10^3$ cm^{-3}. The solid line shows the thretical calculation based on the unified model described above. From the data We can see a clear trend that Γ increases with n. Our model prediction reproduce such a behavior well.

1. The inclusion of infrared and optical component may broaden the ICS γ-ray spectrum without order of magnitude change of the flux.
2. Of course we need an extra normalization factor of each individual source.

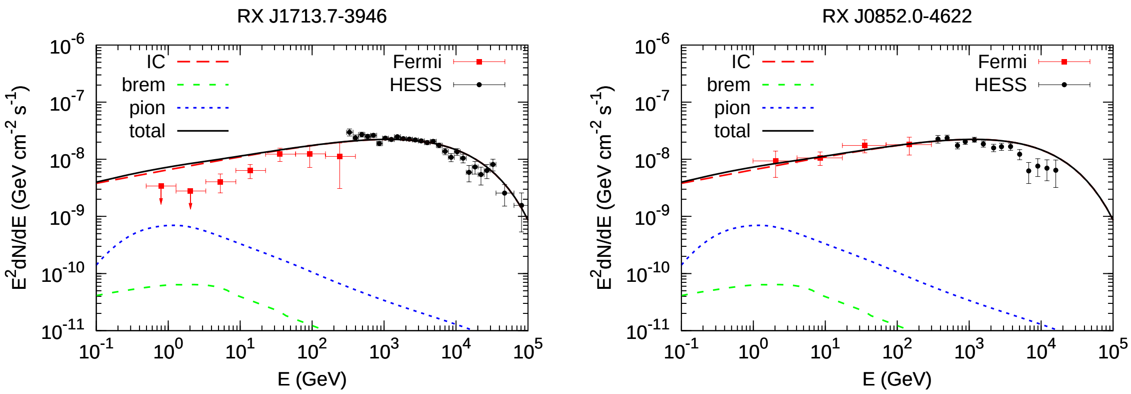

Fig. 2: Expected γ-ray spectra for SNRs RX J1713.7-3946 (left) and RX J0852.0-4622 (right). The gas density is adopted to be $n = 0.01$ cm^{-3}. References of the observational data — RX J1713.7-3946: Fermi [9], H.E.S.S. [30]; RX J0852.0-4622: Fermi [31], H.E.S.S. [32].

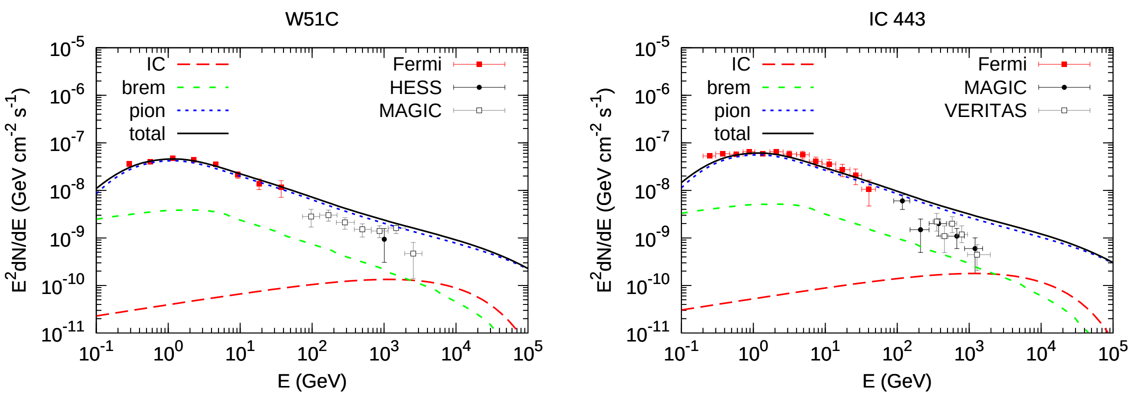

Fig. 3: Expected γ-ray spectra for SNRs interacting with molecular clouds. The left panel is for W51C and the right panel is for IC 443. The gas density is adopted to be $n = 100$ cm^{-3}. References of the observational data — W51C: Fermi [10], H.E.S.S. [33], MAGIC [34]; IC 443: Fermi [15], MAGIC [35], VERITAS [36].

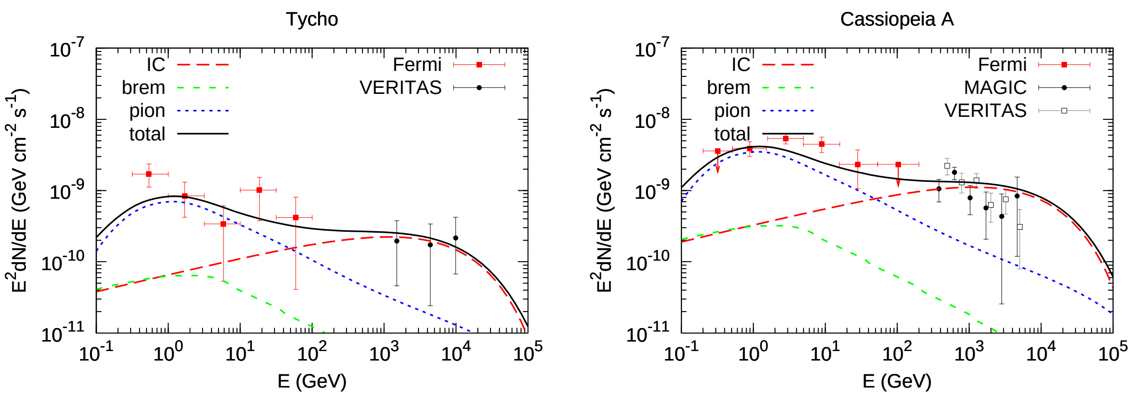

Fig. 4: Expected γ-ray spectra for SNRs Tycho (left) and Cassiopeia A (right). The gas density is adopted to be $n = 1$ cm^{-3}. References of the observational data — Tycho: Fermi [37], VERITAS [38]; Cassiopeia A: Fermi [12], MAGIC [39], VERITAS [40].

From Figs. 2-4 we see that the observed diverse behaviors of the SNR γ-ray spectra can be simply explained by the environmental ISM density. The inferred electron and proton spectra, and K_{ep} value are also consistent with the local CR measurements. It is encouraging that such a unified description may reveal the particle acceleration nature of the SNRs and support the SNR-origin of the Galactic CRs.

Note that we are not dedicated to best-fitting the γ-ray spectra of each source. The spectral parameters of all SNRs are adopted to be the same values in this work. However, we know that there should be dispersion of the param-

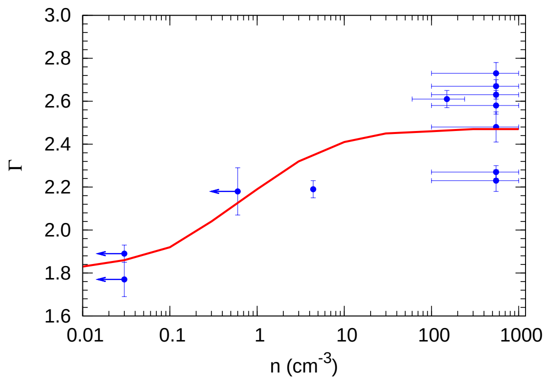

Fig. 5: The photon index Γ (between 1 GeV and 1 TeV) versus the gas density *n* of 12 SNRs. The solid line is the model expected result.

eters of individual source [43]. For the case study of each source, we need to further adjust the paramaters to give better fit to the data [44]. The purpose of this work is to give a *zero*-order approximation of the overall behaviors of the γ-ray emission of SNRs.

4 Conclusions

In this work we propose a unified model to explain the γ-ray emission of SNRs. Based on the assumption that SNRs are the sources of the Galactic CRs (below the "knee"), we derive the injection electron and proton spectra and the electron-to-proton ratio of SNRs according to the locally observed CRs. Applying such results to the SNRs, we find that qualitatively the observed diversity of γ-ray spectra of different SNRs can be naturally understood with different ambient ISM densities. For low density environments the γ-ray emission is ICS dominated, while for high density environments the γ-ray emission is π^0-decay dominated. For some SNRs in the intermediate density environments the γ-ray emission may have a hybrid origin of both π^0-decay and ICS. The model predicts that γ-ray spectra in low density environments are general harder than those of SNR-MC interaction systems. Since strong thermal emission is expected from shocked dense media, we expect relatively weaker thermal emission from remnants with harder γ-ray spectra than those with softer γ-ray spectra. This unified picture self-consistently supports the SNR-origin of the low-energy CRs.

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