Constraining Galactic $p\gamma$ Interactions with Cosmic Ray Electron and Positron Spectra

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Abstract High energy protons produced by various sources of cosmic rays, e.g., supernova remnants, pulsar wind nebulae, active galactic nuclei and gamma-ray bursts, participate in $p\gamma$ and pp interactions. Although pp interactions may be the dominant mechanism in our Galaxy, it is unclear how important $p\gamma$ process is. We show that the upper bound on the fraction of total number of protons participating in $p\gamma$ interactions inside all Galactic astrophysical sources of cosmic rays is 10%.

Key words: Cosmic rays: protons, electrons, positrons

1 INTRODUCTION

High energy protons are expected to be emitted by various astrophysical objects, e.g., supernova remnants (SNRs), pulsar wind nebulae (PWN), microquasars, magnetars, active galactic nuclei (AGN) and gamma-ray bursts (GRBs). The relativistic protons interact with other protons and photons. High energy neutrinos and photons are subsequently produced in these interactions. Neutrinos cannot be produced inside astrophysical sources of cosmic rays if they contain only leptons. Hence, detection of high energy neutrinos from a source would be a signature of the existence of baryons inside that source. Innovative detection methods have been employed in building neutrino detectors (Ackermann et al. 2005; Wischnewski et al. 2005; Aguilar et al. 2006; Katz 2006; Kravchenko et al. 2006; Barwick et al. 2006; Röttgering 2003). The current limit on the diffuse all flavor neutrino flux is 3.3×10^{-7} GeV cm^{-2} s^{-1} sr^{-1} in the energy range of 16 TeV to 2 PeV 2005. In near future a more conservative limit of 4.2×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} or a real detection of the neutrino background is expected from the IceCube Experiment after three years of operation (Ribordy et al. 2005).

Hadrons and leptons are expected to be shock accelerated inside astrophysical objects by the Fermi mechanism to very high energies. Charged and neutral pions can be produced in proton-photon, proton-proton or nucleon-nucleon interactions, and the charged pions subsequently decay to produce neutrinos. Neutrino production interactions are $p\gamma \rightarrow \pi^+ n \rightarrow e^+ \nu_\mu \nu_e \bar{\nu}_\mu n$ and $pp \rightarrow \pi^\pm \rightarrow e^\pm \nu_\mu \nu_e (\bar{\nu}_e) \bar{\nu}_\mu$. We assume pn interactions are similar to pp interactions. The neutral pions decay to γ-rays. It is difficult to know what fractions of all protons in our Galaxy participate in photo-pion ($p\gamma$) production and pp interactions. Unlike neutrinos, the positrons lose energy during their propagation. The propagation of electrons and positrons in our Galaxy has been studied earlier (Moskalenko & Strong 1998). It has been suggested by Anchordoqui et al. (2005) that the detection of Glashow resonance (Glashow 1960) $\bar{\nu}_e$ events at 6.3 PeV by IceCube detector may offer us an opportunity to know whether pp interactions are the dominant mechanisms of ultrahigh energy neutrino production in the universe. The ratios of $\bar{\nu}_e$ to muon flavor neutrinos ($\bar{\nu}_e : (\nu_\mu + \bar{\nu}_\mu)$) at the Glashow resonance energy (6.3 PeV) would be different for neutrinos produced in $p\gamma$ and pp interactions, and by measuring these ratios it would also be possible to estimate neutrino mixing angles at ultrahigh energies (Bhattacharjee & Gupta 2005). However, effects like energy loss by muons is expected

to reduce (Kashti & Waxman 2005) and the decay of μ^- and μ^+ produced in annihilation of secondary photons is expected to enhance the flux of $\bar{\nu}_e$ (Razzaque et al. 2006). These effects make the discrimination between $p\gamma$ and pp sources of neutrinos, by detecting Glashow resonance events, very difficult. Exploring other possibilities to reveal the underlying mechanisms of neutrino production in astrophysical sources is still of great interest. In our Galaxy the major sources of cosmic rays are SNRs and PWN. High energy gamma rays have been detected from many SNRs and PWN (Aharonian et al. 2006) although the leading mechanism (hadronic or leptonic) of γ ray production in these sources is not yet known. They are also expected to be sources of high energy neutrinos (Costantini & Vissani 2005; Kistler & Beacom 2006; Kappes et al. 2007; Vissani 2006). The gamma ray flux detected by CANGAROO from SN 1006 has been fitted with the theoretical model of π^0 decay (Ksenofontov et al. 2005). The flux produced in inverse Compton scattering of electrons by low energy photons is much lower than that produced in π^0 decay. Recently, evidence of hadronic origin of gamma rays from Vela X (Horns et al. 2006) and PSR B1259–63 (Neronov & Chernyakova 2006) has been reported. If a gamma ray energy flux of $2 \times 10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ is detected from SN 1987A in the energy range of 0.1 to 10 TeV then it would imply that these gamma rays are of hadronic origin produced in π^0 decay (Berezhko & Ksenofontov 2006). The neutrino fluxes expected from various PWN were calculated (Bednarek & Protheroe 1997; Bednarek 2006) for a detailed modeling of the sources and found to be detectable in some cases by large scale neutrino telescopes of km^2 area. High energy neutrino emission from $p\gamma$ process inside the magnetospheres of isolated neutron stars has been discussed for magnetars (Zhang et al. 2003) and for young pulsars (Link & Burgio 2006). The subject of our discussion in this paper is whether it is possible to constrain the parameter x, the fraction of the total number of Galactic protons participating in $p\gamma$ interactions.

2 DIFFUSE ELECTRON AND POSITRON SPECTRA

Since high energy electrons and positrons lose energies faster than other charged particles in various energy loss mechanisms, e.g., bremsstrahlung, synchrotron emission and inverse Compton scattering, their observed fluxes are most likely of Galactic origin. Above 1 GeV the dominant energy loss processes are inverse Compton and synchrotron. It has been discussed (Berezinsky et al. 1990) that approximately 10% of electrons and all positrons are secondary particles produced in nuclear interactions. There are some discrepancies in the measured data on electrons and positrons. The large spread above several GeV in the data cannot be explained as an effect of solar modulation. Systematic errors in the measurements might be responsible for the disagreement in the data taken by different experimental groups. Müller (2001) and Du Vernois et al. (2001) suggested rescaling of the upper set of data points to match the electron flux at 20 GeV obtained with the best fit of the lower set of data points that include the recent results of the AMS experiment (Alcaraz et al. 2000). After the rescaling, all the data points in the energy range of 3 GeV to 2 TeV can be fitted with a single power law with spectral index 3.44 ± 0.03 (Casadei & Bindi 2004). With a similar procedure of renormalization of the data from MASS 89 (Golden et al. 1994) and MASS 91 (Grimani et al. 2002) experiments, the positron data points can be fitted with a single power law with spectral index 3.43 ± 0.05 above 0.7 GeV. The single power law fitted spectra are shown in figures 4 and 5 of Casadei & Bindi (2004), and we have used their results in the present paper.

3 PROTON INTERACTIONS AND ELECTRON, POSITRON FLUXES

Cosmic rays with energies up to 10^{18} eV are most likely of Galactic origin. Protons can be accelerated to very high energies inside Galactic cosmic ray sources, e.g., SNRs, PWN, and microquasars. One interesting feature is that interactions of shock accelerated protons with photons ($p\gamma \rightarrow e^+\nu_\mu\bar{\nu}_\mu\nu_e n$) leading to the production of neutrinos generate high energy positrons, but not electrons. Most other processes, on the other hand, produce equal number of electrons and positrons through pairs. These processes include $p\gamma \rightarrow pe^+e^-$, $pp \rightarrow e^\pm\nu_\mu\bar{\nu}_\mu\nu_e(\bar{\nu}_e)$ and $\gamma\gamma \rightarrow e^+e^-$. Such an asymmetry makes it possible to estimate the contribution of $p\gamma$ process through evaluating the measured e^+ and e^- fluxes.

The shock accelerated electron and proton spectra inside the sources could be approximated as power laws in energy with similar spectral index, i.e., $S_{e^-}(E_e) = A_e E_e^{-\alpha}$ and $S_p(E_p) = A_p E_p^{-\alpha}$. The possible values of α can be calculated by numerical simulations (Lemoine & Pelletier 2003). Electrons and positrons lose energy faster than protons inside the sources. We discuss in Section 4 how the internal magnetic field and size of a source determine the escape probability of electrons and positrons from the

source. We denote the electron and positron spectra injected into the Galaxy as $Q_{e^-}(E_e)$ and $Q_{e^+}(E_e)$ respectively. During propagation the cosmic ray protons and nucleons would mainly interact with Galactic matter and produce secondary electrons and positrons, since the Galactic diffuse gamma-ray background is not high enough for significant positron production by the propagating cosmic rays through $p\gamma$ interactions at the Δ resonance. The solution of the transport equation for the propagation of $e^{\pm}$ in the Galaxy is $N(E_e) \approx Q(E_e)V_{\text{source}}\tau(E_e)/V_{\text{occ}}(E_e)$, where $Q(E_e)$ is the source flux, V_{source} is the volume of the sources, $V_{\text{occ}}(E_e)$ is the volume in the Galaxy occupied by electrons or positrons of energy E_e, and $\tau(E_e)$ is the lifetime of the particle with energy E_e (Berezinsky et al. 1990). We assume that out of the total number of protons inside all Galactic astrophysical objects, a fraction x participates in $p\gamma$ interactions to produce neutrinos, another fraction y participates in pp interactions and the rest z escapes without any interactions or produce $e^{\pm}$ pairs in $p\gamma$ interactions, with $x + y + z = 1$. The injection source fluxes of electrons and positrons can be expressed as

$$Q_{e^-}(E_e) = P_{e^-}(E_e) + F(E_e) , \tag{1}$$

$$Q_{e^+}(E_e) = xf\phi_{p\gamma \to \nu + e^+}(E_e) + F(E_e) . \tag{2}$$

Here $F(E_e)$ denotes the secondary electron or positron flux injected into the Galaxy from all the interactions in which electron and positron pairs are produced, both inside the astrophysical sources and during the propagation of the protons and nucleons in the Galaxy. Rotation-powered pulsars inject electron-positron pairs from the magnetosphere through magnetic one-photon ($\gamma B \to e^+e^-$) pair production processes (Ruderman & Sutherland 1975; Daugherty & Harding 1982; Zhang & Harding 2000). WIMP annihilations also generate electron-positron pairs (Tylka 1989). All these processes are included in our $F(E_e)$ terms. We assume that the astrophysical sources contain protons and electrons, but the positrons are produced only in the interactions. Thus we denote $P_{e^-}(E_e)$ as the primary diffuse electron flux directly injected from all the Galactic astrophysical objects (not generated through interactions). In Equation (2), $\phi_{p\gamma \to \nu + e^+}(E_e)$ is the positron flux produced in photo-pion interactions normalized to one pion per nucleon ($p\gamma \to \pi^+ n \to e^+ \nu_\mu \nu_e \bar{\nu}_\mu n$) inside all astrophysical sources, *assuming* that all protons participate in $p\gamma$ interactions to produce neutrinos. The positrons produced in this way lose energies by bremsstrahlung, synchrotron and inverse Compton mechanisms before their escape from the sources. The emitted fluxes are related to the fluxes produced inside the sources by a factor $f \leq 1$. This factor accounts for the escaping probability and energy losses of electrons and positrons. The factor x denotes the fraction of protons which participate in $p\gamma$ interactions to produce neutrinos. If $x = 0$ there is no neutrino production through $p\gamma$ interactions inside the sources, and $x = 1$ if all the neutrinos are produced in $p\gamma$ interactions. One can then relate the observed and source fluxes of electrons and positrons through the following ratios,

$$\frac{N_{e^-}(E_e) - N_{e^+}(E_e)}{N_{e^-}(E_e)} = \frac{Q_{e^-}(E_e) - Q_{e^+}(E_e)}{Q_{e^-}(E_e)} = \frac{P_{e^-}(E_e) - xf\phi_{p\gamma \to \nu + e^+}(E_e)}{P_{e^-}(E_e) + F(E_e)} . \tag{3}$$

Besides $p\gamma$ interactions, all other interactions discussed earlier, e.g., pp, $\gamma\gamma$, γB, WIMP annihilations, generate equal fluxes of electrons and positrons. The observed positron flux is about 10% of the observed electron flux and they are expected to be produced in various interactions (pp, $p\gamma$, etc.) as discussed earlier. Hence, it is reasonable to assume that the flux of secondary electrons produced in interactions inside astrophysical sources and inside the Galaxy during the propagation of the cosmic rays is much less compared to their original flux which is not produced in any interaction (Berezinsky et al. 1990). From this argument it follows that $F(E_e) << P_{e^-}(E_e)$. In $p\gamma$ interactions charged and neutral pions are produced with almost equal probabilities. Unlike positrons, the nucleons produced in $p\gamma$ interaction escape from the sources before losing their energies significantly. The charged pion carries about 20% of the initial proton's energy and the final state leptons share the energy of π^+ equally. The energy E_p of the proton and the energy E_e of the positron produced in one $p\gamma \to \pi^+ n \to e^+ \nu_e \nu_\mu \bar{\nu}_\mu n$ interaction are related: $E_e = \frac{1}{5} \times \frac{1}{4}E_p$. The total energies carried by all the positrons of energy E_e produced in $p\gamma$ interactions and all the protons of energy E_p are related (Waxman & Bahcall 1999),

$$E_e^2 \phi_{p\gamma \to \nu + e^+}(E_e) = \frac{1}{2} \times \frac{1}{5} \times \frac{1}{4}E_p^2 A_p E_p^{-\alpha}, \tag{4}$$

where $A_p E_p^{-\alpha}$ is the shock accelerated proton number flux per unit energy (at dE_p) inside the sources of cosmic rays, and the factor $1/2$ takes into account the contribution of protons that produce π^0 (and hence, not contributing to the e^+ production). The positron flux produced in $p\gamma$ interactions can be then expressed as

$$\phi_{p\gamma\to\nu+e^+}(E_e) = \frac{A_p}{40}\frac{E_p^{2-\alpha}}{E_e^2}. \tag{5}$$

Equation (3) can then be expressed in terms of the spectral index α, the lepton energy E_e,

$$\begin{aligned}
\frac{N_{e^-}(E_e) - N_{e^+}(E_e)}{N_{e^-}(E_e)} &= \frac{P_{e^-}(E_e) - xf\phi_{p\gamma\to\nu+e^+}(E_e)}{P_{e^-}(E_e) + F(E_e)} \\
&\approx \frac{P_{e^-}(E_e)}{P_{e^-}(E_e) + F(E_e)} - \frac{xf\phi_{p\gamma\to\nu+e^+}(E_e)}{\left[1 + r(E_e)\right]fA_e E_e^{-\alpha}},
\end{aligned} \tag{6}$$

where, we have used $P_{e^-}(E_e) + F(E_e) = Q_{e^-}(E_e)$ from Equation (1) and the ratio of observed positron and electron fluxes (Casadei & Bindi 2004; Aguilar et al. 2007), $r(E_e) = N_{e^+}(E_e)/N_{e^-}(E_e)$. $Q_{e^-}(E_e)$, can be greater than $fS_{e^-}(E_e)$ (the diffuses electron flux emitted from all Galactic sources) by at most a factor of $[1 + r(E_e)]$. We have replaced $Q_{e^-}(E_e)$ with $[1 + r(E_e)]fS_{e^-}(E_e)$ in the denominator of the second term on the right hand side of Equation (6). The positron's energy E_e and the proton's energy E_p are related: $E_e = E_p/20$. Assuming that the shock accelerated electrons of mass m_e and protons of mass m_p have the same values of spectral indices the ratio of their shock accelerated fluxes at relativistic energies $(E > m_p c^2)$ is $\frac{A_e}{A_p} = \zeta\left(\frac{m_e}{m_p}\right)^{(\alpha-1)/2}$ (Berezinsky et al. 1990) where ζ is the ratio of the non relativistic electron and proton fluxes at any energy $E_k < m_e c^2$ (for non relativistic particles it is the kinetic energy). The numbers of non relativistic primary electrons and protons inside the sources are expected to be equal hence, $\zeta \sim 1$. We can then constrain x using the following expression,

$$x \approx 40\Big[1 + r(E_e)\Big] \times \left(\frac{1}{20}\right)^{2-\alpha}\left(\frac{m_e}{m_p}\right)^{\frac{\alpha-1}{2}}\left[r(E_e) - \frac{F(E_e)}{P_{e^-}(E_e) + F(E_e)}\right]. \tag{7}$$

The ratio of observed positron and electron fluxes $r(E_e)$ is available from observed data. However, we do not know how large the ratio $F(E_e)/[P_{e^-}(E_e) + F(E_e)]$ is. Assuming $F(E_e) = 0$, one can put an upper bound on x,

$$x \le 40\Big[1 + r(E_e)\Big] \times \left(\frac{1}{20}\right)^{2-\alpha}\left(\frac{m_e}{m_p}\right)^{\frac{\alpha-1}{2}}r(E_e). \tag{8}$$

Thus it is possible to constrain x using the observed data on positron and electron fluxes.

4 RESULTS

The current data on cosmic ray positron flux is up to about $60\,\mathrm{GeV}$. In Aguilar et al. (2007) the data are given up to $30\,\mathrm{GeV}$. Below $10\,\mathrm{GeV}$ solar modulation effect becomes important hence we have considered the energy range above this energy. As the ratio of the measured fluxes of positrons and electrons is small the errors involved in current measurements of this ratio affect the result. In future with more precise measurements the flux ratio could be determined more accurately. The average value of the observed flux ratios is 0.1. We calculate the upper bound on x for an energy range of $10\,\mathrm{GeV}$ to $60\,\mathrm{GeV}$ using the power law fit to the compilation of data from Casadei & Bindi (2004). Our result is

$$x \le 10\% \tag{9}$$

for $\alpha = 2.1 - 2.4$. The upper limit on x slightly decreases with increasing α. In general the factor x depends on energy, but in the $10 - 60\,\mathrm{GeV}$ range it is insensitive to the energy if we use the power law fit to the compiled data from Casadei & Bindi (2004). In future it would be possible to constrain x at higher energies when positron fluxes at higher energies are available.

5 DISCUSSION

In Equation (3) we introduced the f parameter, i.e. the escaping factor of the generated positrons through $p\gamma$ processes. Our derived lower limit of x (Eq. (8)) does not depend on f. In any case, it is interesting to discuss the possible value of f. In order to contribute to the observed positron flux at earth, the positrons must not cool before escaping the source. This requires that the cooling time scale t_{cool} is longer than the escaping time scale t_{esc}. For standard synchrotron and its self-Compton (SSC) cooling, the cooling time scale can be estimated as

$$t_{\text{cool}} = \frac{m_e \gamma_e c^2}{\frac{4}{3}\sigma_{\text{T}} c \gamma_e^2 \frac{B^2}{8\pi}(1+Y)}, \tag{10}$$

where m_e is the mass of a positron, c the speed of light, γ_e the Lorentz factor of the positron, B the internal magnetic field of the source, σ_{T} the Thomson cross section, and Y the ratio between the synchrotron photon energy density and the magnetic field energy density. The typical values of B required to explain the observed radio and X-ray data from SN 1006 and SN 1987A are about $150\,\mu$G (Ksenofontov et al. 2005) and $10\,$mG (Berezhko & Ksenofontov 2006), respectively, which is close to the equilibrium value. According to Yamazaki et al. (2006), SSC is important only if the magnetic field is much lower than $1\,\mu$G. As a result, the Y parameter is at most of order unity, and the SSC process is not expected to be the dominant cooling mechanism of electrons and positrons inside Galactic sources of comsic rays.

To estimate the escaping time scale, we adopt the random walk approximation. In a random magnetic field, the mean free path for each scattering may be estimated as the Larmor radius R_{L}. The number of scattering of a positron before escaping the source is $\sim (\frac{R}{R_{\text{L}}})^2$, where R is the radius of the region of particle acceleration inside the source. We therefore have

$$t_{\text{esc}} = \left(\frac{R}{R_{\text{L}}}\right)^2 \frac{R_{\text{L}}}{c}. \tag{11}$$

Since $R_{\text{L}} = \frac{m_e \gamma_e c^2}{eB}$, it is interesting to observe that t_{cool} and t_{esc} have the same γ_e dependence. This suggests that for a particular source, either all positrons escape the source ($t_{\text{cool}} > t_{\text{esc}}$) or all positrons cool before escaping ($t_{\text{cool}} < t_{\text{esc}}$). With Equations (10) and (11), the positron-escaping condition is

$$B_{-3}(1+Y)^{1/2} \leq 3.4 R_{15}^{-2/3}, \tag{12}$$

where the convention $Q_i = Q/10^i$ in cgs units is adopted. The size of the positron emission region may vary from source to source. We can see that this condition is marginally satisfied by the cosmic sources, that, generally, we expect some sources can satisfy Equation (12) and contribute to the observed diffuse positron spectra. The factor f is energy-independent, and hence, does not enter the problem of constraining x.

In summary, with the current data one can derive an upper bound on the fraction of Galactic protons that participate in $p\gamma$ interactions in our Galaxy, and the upper bound is 10%. Our current result is relevant to the positron energy range between $10\,$GeV to $60\,$GeV. In future it may be possible to extend our results with more observational data on positron fluxes at higher energies.

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