MUON ACCELERATION IN COSMIC-RAY SOURCES

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ABSTRACT

Many models of ultra-high energy cosmic-ray production involve acceleration in linear accelerators located in gamma-ray bursts, magnetars, or other sources. These transient sources have short lifetimes, which necessitate very high accelerating gradients, up to $10^{13}$ keV cm$^{-1}$. At gradients above 1.6 keV cm$^{-1}$, muons produced by hadronic interactions undergo significant acceleration before they decay. This muon acceleration hardens the neutrino energy spectrum and greatly increases the high-energy neutrino flux. Using the IceCube high-energy diffuse neutrino flux limits, we set two-dimensional limits on the source opacity and matter density, as a function of accelerating gradient. These limits put strong constraints on different models of particle acceleration, particularly those based on plasma wake-field acceleration, and limit models for sources like gamma-ray bursts and magnetars.

Key words: acceleration of particles – astroparticle physics – magnetic fields – neutrinos – relativistic processes

Online-only material: color figures

1. INTRODUCTION

For more than 100 yr, scientists have investigated cosmic rays (CRs) and their origin. Up to energies of $\sim$5 PeV, CR production may be adequately described by current models of acceleration in supernova remnants. At ultra-high energy (UHE), however, the acceleration mechanism is still unknown.

Many sources have been proposed, such as active galactic nuclei (AGNs), and transient sources like gamma-ray bursts (GRBs) and magnetars, with lifetimes from seconds to a few days. Typically, acceleration involves repeated diffusive shock acceleration, at a site where a magnetic field confines the particles (Fermi 1949; Bell 1978a, 1978b; Schlickeiser 1989a, 1989b; Meli et al. 2008).

The maximum CR energy and the requisite short time scales require very large accelerating gradients. Several authors have proposed single-pass linear accelerators (Tajima & Dawson 1979; Buckley 1977; Chen et al. 2002; Arons 2003; Chang 2009; Kotera 2011; Fang et al. 2012), often in a relativistic jet, such as those emerging from GRBs or AGNs.

The required accelerating gradients may be provided by a couple of mechanisms. Plasma wake-field acceleration (PWA) in astrophysical settings may allow for gradients up to $\approx 10^{11}$ eV cm$^{-1}$ (Chen et al. 2002; Chang 2009). PWA might be possible at a variety of accelerating sites, including GRBs and AGNs. Magnetars, newborn neutron stars with enormous (petagauss) magnetic fields, also allow acceleration with very high gradients. In magnetars, the acceleration occurs in the first few seconds of the magnetar’s life, as it dissipates its rotational energy (Arons 2003).

One technique to locate UHE acceleration sites is to search for neutrinos that point back to their production site. The neutrinos come from the decay of pions and kaons which are produced when CRs interact with nuclei or photons in the source. Neutrinos are produced largely from $\pi^\pm$ or $K^\pm$ decay via the chain reactions like $\pi^+ \rightarrow \mu^+ \nu_\mu$, followed by $\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$. Typically, neutrinos are produced in a ratio $\nu_e: \nu_\mu: \nu_\tau \approx 2:1:0$ but oscillate to $\sim 1:1:1$ before they reach Earth (Becker 2008). Here, we give the decay chains for $\pi^+$ to differentiate between the $\nu_\mu$ from the pion decay and the $\nu_\mu$ from the muon decay; the latter is affected by muon acceleration, but the former is not. Further, $\pi^-$ are produced in similar numbers, and their decay products are equivalently affected.

The neutrino flux depends on the flux of the accelerated CRs and on the number of times they interact during acceleration (Gaisser 1990). Most calculations of neutrino production in CR accelerators use the measured CR flux and assumptions about the CR composition and nuclei/photon target density in the source to predict the neutrino flux that should be seen in terrestrial detectors. The production is presumed to largely occur near threshold, so that the neutrino energy spectrum is similar to that of the original proton spectrum (Waxman & Bahcall 1998). Prompt neutrino production is mainly a factor at very high energies, above 1 PeV for current GRBs (Enberg et al. 2008). This neutrino flux is affected by two factors.

First, muon energy loss, which is likely dominated by synchrotron radiation; considered important at energies above $10^{17}$ eV (Waxman & Bahcall 1997; Kashti & Waxman 2005; Hümmer et al. 2010). Photomeson production may also be important (Murase & Nagataki 2006).

The second factor is muon acceleration. At large accelerating gradients, muons gain energy before decaying, altering the neutrino energy spectrum and flavor composition. This was considered for choked GRBs in Koers & Wijers (2007). When the energy gain is large enough, the neutrino flux is enhanced significantly.

We study the effect of muon acceleration and energy loss on neutrino production, and we determine the limiting energies and the enhanced fluxes. We use existing neutrino flux limits to set limits on the maximum source opacity, as a function of accelerating gradients, under the assumption that these sources are the sites of CR acceleration. We also present limits on particle density in sources, under the same assumption.
2. MUON ACCELERATION AND ENERGY LOSS

First, we look at the energy gain by a muon with Lorentz boost $\gamma$ (throughout, we assume $\gamma \gg 1$). In an accelerating gradient $g$, the muon gains energy at a rate

$$\frac{dE}{dt} = gc. \quad (1)$$

Assuming a constant $g < g_0 = m_\mu/c\tau_\mu \approx 1.6$, then the energy gained by the muon is given by the accelerating gradient times the distance covered by the muon before decay,

$$\Delta E = g\gamma c\tau_\mu, \quad (2)$$

where $\tau_\mu$ is the muon lifetime. With larger gradients, $\gamma$ increases during the acceleration (in the laboratory frame of reference). The average final energy $E_f$ is then a multiple of the initial energy $E_i$:

$$E_f = E_i e^{g\gamma c\tau_\mu/m_\mu}, \quad (3)$$

where $m_\mu$ is the muon mass. These equations also apply for pions, with the appropriate mass and lifetime substitutions. Because the charged pion lifetime $\tau_\pi$ is about 1% of $\tau_\mu$, pion acceleration is only relevant at 100 times higher gradients than for muons. For small gradients, the muon energy does not change significantly before it decays.

Muons lose energy by synchrotron radiation and by interacting with matter or photons. Muon interactions with matter are far weaker than for protons, with a typical range more than 100 times higher than the proton interaction length. So, we neglect muon interactions with matter.

In photon-dominated regions, muons lose energy by pair conversion and inverse Compton scattering. These losses are usually smaller than those experienced by protons, which predominantly lose energy by photoexcitation to a $\Delta$ resonance.

We assume that, in any environment where protons are accelerated, muon energy loss is dominated by synchrotron radiation. The energy loss in a magnetic field $B$ at an angle $\theta$ to the direction of motion of a muon with Lorentz boost $\gamma$ in cgs units is

$$\frac{dE}{dt} = \frac{2}{3} \frac{e^4}{m_\mu^2 c^2} \gamma^2 B^2 \sin^2(\theta). \quad (4)$$

When the magnetic field and direction of motion are parallel, there is no synchrotron radiation energy loss. The angle may depend on a detailed source model; here, we will take an average (in 3-space) so that $\langle \sin^2(\theta) \rangle = 2/3$.

In the presence of acceleration and energy loss, muons reach an equilibrium energy $E_e$ at which energy gain and loss are equal. For synchrotron radiation, this energy is obtained by equating Equations (1) and (4),

$$E_e = \frac{3}{2} \left( \frac{m_\mu c^2}{e} \right)^2 \frac{\sqrt{g}}{B}. \quad (5)$$

Figure 1 shows how particles gain energy at a constant rate until they reach $E_e$. Any accelerator that produce $10^{20}$ eV protons can also support $10^{16}$ eV pions and muons. This is a minimum constraint; if energy loss is dominated by interactions with matter or photons, then $E_{\mu,\max}/E_{p,\max}$ will be higher.

3. NEUTRINO PRODUCTION

Any viable CR accelerator model must be able to explain the observed energy spectrum of CRs. Fermi shock acceleration, for example, leads to an $E^{-2}$ spectrum at the source (Gaisser 1990). This spectrum can be steepened by diffusion during propagation to a $E^{-2.7}$ spectrum ($E^{-3}$ at energies above a few PeV). During acceleration, CRs interact with matter or photons. Secondary particles produced in both processes approximately reproduce the spectral behavior of the primary spectrum above a certain threshold. While this threshold lies in the MeV range for interactions with matter, it depends on the spectral energy distribution of the photon field in case of photohadronic interactions, e.g., see Waxman & Bahcall (1998) and Mannheim & Schlickeiser (1994). When secondary pions decay, three neutrinos and an electron are produced: $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^- \nu_e \nu_\mu$ ($\nu_\mu$). These approximately share the energy of the original pion equally (Becker 2008).

In a strong accelerating gradient, however, secondaries are accelerated and the spectra of primary and secondary particles no longer show the same spectral behavior. While muon acceleration alters the energy of the two neutrinos from the muon decay, then pion acceleration affects all of the final state particles. At low energies, energy gain dominates, while at high energies, flux suppression due to synchrotron radiation is expected.

3.1. Numerical Results

In our model calculations, we assume that protons are accelerated following an $E^{-2}$ spectrum, up to a cutoff energy of $10^{20}$ eV. Hence we assume that secondary pions are produced with an $E^{-2}$ spectrum as well. From this initial spectrum, we determine the energy spectrum when the pions decay, allowing for energy gain or loss, considering both $\pi^+$ and $\pi^-$. The resulting muons are then followed in the same manner. This process effectively shifts the energy at which the neutrinos are produced and may lead to neutrino flux enhancement or suppression at different energies.

Figure 2 shows the enhancement of neutrino spectrum for three accelerating gradients, including energy loss due to synchrotron radiation. They are compared to an un-enhanced spectrum calculated without energy loss. Panels (a)–(c) are for an $E^{-2}$ spectrum. Panel (a) shows the enhancement for the three different flavors for a gradient of 0.5 keV cm$^{-1}$ ($\approx g_0/3$) in a 1000 gauss magnetic field. Muon neutrinos are unaffected (since
For these gradients, pion acceleration is negligible. At much larger gradients, \( g > m_\pi c/\tau_\pi \approx 160 \text{ keV cm}^{-2} \), pion acceleration would be important, and the \( \nu_\mu \) curve would show similar alterations.

This analysis neglects the possibility of muons or pions escaping from the source before decaying. Inclusion of the escape probability would moderate the increase in neutrino flux, depending on the relative probability of escape or decay.

While low-energy pions are produced at the beginning of the acceleration cycle, high-energy pions are produced near the end of the accelerator. This results in an asymmetry in the amount of distance within the accelerator covered by low- and high-energy secondaries. This could give an energy dependence to the amount of secondary acceleration. However, the present results show that the flux enhancement is almost solely due to acceleration of low-energy secondaries and not much affected by the deceleration of high-energy secondaries. This is largely a result of the steep \( E^{-2} \) spectrum. It is therefore of no importance for our conclusions.

4. LIMITS ON OPACITY, TARGET DENSITY AND ACCELERATING GRADIENTS

Some \( \nu \) flux calculations are based on specific source models, while others are more generic, tied to the measured UHE CR flux (Waxman & Bahcall 1998), or the TeV photon fluxes observed by air Cherenkov telescopes. Current diffuse \( \nu \) flux limits are near or below the more optimistic flux predictions (Abbasi et al. 2011; Dzhilkibaeva 2009; Biagi 2011). For model-independent searches (Abbasi et al. 2011), this also concerns afterglow emission (Waxman & Bahcall 2000) and choked GRBs (Meszaros & Waxman 2001).

We use the IceCube diffuse \( \nu \) flux limits to set two-dimensional limits on the source opacity and accelerating gradients. The source opacity, \( \delta \), treatment follows (Waxman & Bahcall 1998), relating neutrino production in an accelerator to the matter/photon density in the accelerator.Opacity is defined as the fraction of proton energy that is lost due to proton–proton or proton–photon interactions in the target. Waxman and Bahcall set an upper limit \( \delta = 1 \), corresponding to a neutrino flux \( (\phi) \) limit for an \( E^{-2} \) spectrum, of \( \phi_{\nu B} = E^2\phi < 2.0 \times 10^{-8} \text{ GeV/(cm}^2 \text{ s sr)} \), beyond which protons will not emerge from the acceleration site.

While here we focus on using neutrino limits to constrain matter densities, photodisoc interactions are extremely important in GRBs (Waxman & Bahcall 1997; Guetta et al. 2004; Becker et al. 2006). In choked GRBs, radiation fields also contribute to pion and muon interactions (Razzaque et al. 2003). Without considering muon acceleration, interactions with radiation fields have been tested with IceCube (Abbasi et al. 2012). As discussed here, modeling photodisoc interactions depends on a number of parameters, the most important being the Lorentz boost factor of the moving shock and the ratio of electrons to protons. An interpretation of the neutrino flux limits for photodisoc interactions is therefore more complicated compared to the case of proton–proton interactions. The investigation of limiting physical parameters with muon acceleration from photodisoc interactions will therefore be subject to investigation in future work.

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\( g > m_\pi c/\tau_\pi \approx 160 \text{ keV cm}^{-2} \)

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\( \phi_{\nu B} = E^2\phi < 2.0 \times 10^{-8} \text{ GeV/(cm}^2 \text{ s sr)} \)
We use the IceCube 40-string diffuse $v_\mu$ flux limit (Abbasi et al. 2011). For an $E^{-2}$ spectrum, the 90% confidence level limit is $E_\nu^3 \phi_{IC} = \phi < 8.9 \times 10^{-5} \text{GeV}/(\text{cm}^2 \text{s sr})$.

Because muon acceleration changes the $v$ spectral index, one cannot directly use the IceCube limit. However, Figure 5 in Abbasi et al. (2011) gives the effective area for the search, defined so that the number of detected events is

$$N = \int dE_\nu d\Omega d\Omega E_\nu \phi(E_\nu) A_{\text{eff}}(E_\nu).$$

Equation (6) for a neutrino flux at the IC40-limit to determine the number of neutrino events $N_{\text{needed}}$ required for IceCube to see a signal.

The IceCube 90% confidence level limit corresponds to an opacity, $O_{IC} = \phi/\phi_{WB} < 0.4$. This limit applies at low accelerating gradients; at larger gradients, muon acceleration increases the flux and lowers the allowed opacity. Figure 3 shows two-dimensional limits on $O$ and $g$. For $g > 5 \text{ keV cm}^{-1}$, the opacity must be below $10^{-8}$, a very severe constraint.

The opacity limit may be used to set a bound on the matter density in a source; for matter dominated interactions

$$O = \sigma \rho L,$$

where $\sigma$ is the inelastic interaction cross-section, $\rho$ is the matter density, and $L = E_{p,\text{max}}/g$ is the length of the accelerator. We assume that the matter is hydrogen, and take $\sigma = 100 \text{ mb}$ independent of energy. The actual cross-section rises slowly with energy, but $100 \text{ mb}$ is a reasonable approximation here (Antchev et al. 2011). The limit on source density as a function of accelerating gradient is shown in Figure 4. At low accelerating gradients, the accelerator is long, and

$$\rho < \frac{O_{IC}}{\sigma E_{p,\text{max}}} \approx 4 \times 10^7 \text{ cm}^{-3} \left(\frac{g}{1 \text{ keV cm}^{-1}}\right).$$

At very high gradients, muon and pion acceleration dominate the flux, and the density limit depends only slightly on the gradient. For accelerating gradients $g > 5 \text{ keV cm}^{-1}$, the source density must be less than $2 \times 10^6 \text{ cm}^{-3}$.

These limits are on the matter density within the accelerating region. Outside the accelerating region (i.e., in a surrounding gas cloud), higher densities are possible as well as cases where matter is coaccelerated, and there is basically no resting target toward the CRs. However, as will be seen below, many models require matter to support the acceleration mechanism. The calculations also assume that the accelerating gradient, magnetic field and source density are constant. Allowing for a non-uniform accelerating gradient, magnetic field or source density would alter the limits, but not by a large factor. Another uncertainty comes from the treatment of the $\pi$ production threshold. Our treatment is standard (Waxman & Bahcall 1998), but acceleration enhances the importance of the threshold behavior.

5. CONSTRAINTS ON ACCELERATION MODELS

These limits on $g$, $O$, and $\rho$ can be used to constrain several models of CR acceleration. The enhancement shown in Figure 2 does not drain the CR source if the opacity/density is simultaneously lowered according to the limits on Figures 3 and 4.

Plasma wave acceleration models predict very high accelerating gradients and at the same time require a significant plasma density, which is high enough to violate Equation (8). For example, in Chen et al. (2002), a $10^{13} \text{ keV cm}^{-1}$ accelerating gradient requires a density of $\approx 10^{20} \text{ cm}^{-3}$ in the case of a GRB. At $10^{13} \text{ keV cm}^{-1}$, the maximum allowable source density (within the neutrino flux limits) is less than $2 \times 10^6 \text{ cm}^{-3}$. In Chang (2009), the same PWA mechanism is applied to an AGN requiring an accelerating gradient of $0.1 \text{ keV cm}^{-1}$ and a density of $10^{10} \text{ cm}^{-3}$. Neither of these models is compatible with UHE CR production.

GRBs have durations of tens of seconds or less. This requires a very compact emission region which argues strongly for a compact accelerator with high accelerating gradients. In the fireball model, shock acceleration occurs in a fireball which is moving at relativistic speed. CRs are emitted in the direction of the highly relativistic jets. The fireball’s Lorentz boosts, $\Gamma_f$, are estimated to be in the range from a few, up to about 1000, e.g., see Abdo et al. (2009). Assuming that UHE CR come from the prompt phase of the GRB, the acceleration happens within the $\sim 100 \text{ s}$ long prompt phase (Waxman 1995). Setting $\Gamma_f \sim 300$, the accelerating gradient in the lab frame is of the order of

$$\frac{E_{\nu,\text{max}}'}{t_{90} c} = \frac{E_{\nu,\text{max}}}{\Gamma_f t_{90} c} \sim 30 \text{ keV cm}^{-1},$$

where $E_{\nu,\text{max}}'$ is the maximum energy in the fireball frame of reference, and $t_{90}$ and $t_{90}'$ are the time containing 90% of the gamma-ray emission in the laboratory and fireball frames of reference, respectively. Muon and pion acceleration are both important. The present results show that at an energy of 10 TeV, a $30 \text{ keV cm}^{-1}$ gradient raises the neutrino flux.
regions with large electric fields, but low magnetic fields (Arons 2003). Other models may lead to lower fluxes, e.g., see He et al. (2012), Li (2012), and Hümmert et al. (2012). However, accelerating gradients larger than 30 keV cm$^{-1}$ would certainly have raised the neutrino flux to the point where it would be easily detectable by IceCube, at least for models where the neutrinos come from pion decay. The neutrino flux limits appear inconsistent with large accelerating gradients imposed by the length of the prompt phase. For linear acceleration, it is simple to see that the concept fails in this case. These limits also apply to stochastic acceleration, as long as one acceleration cycle needs to rely on gradients of the order of 30 keV cm$^{-1}$ or larger. This requirement may apply if the acceleration efficiency per cycle is large enough. It will be interesting to investigate further in the future following the work of Murase et al. (2012 and references therein).

Magnetars are newly formed neutron stars with magnetic fields up to $10^{15}$ gauss. The acceleration of CRs may occur in regions with large electric fields, but low magnetic fields (Arons 2003). The limited size of these regions (≈30,000 km) require gradients of $3 \times 10^7$ keV cm$^{-1}$. If magnetars are the primary sources of UHE protons, $10^{16}$ eV muons are produced. At a gradient of $3 \times 10^7$ keV cm$^{-1}$, muon acceleration would greatly magnify the neutrino flux. This precludes magnetars as being the dominant source of UHE CRs unless the matter density at the acceleration site is very low, less than $2 \times 10^7$ cm$^{-3}$. In the model presented in Arons (2003), a highly clumped medium is assumed to be caused by the wind of the pulsar, which may lead to a relatively low density and might still allow for the acceleration of protons without significant muon production. In Fang et al. (2012), the entire plasma is assumed to be coaccelerated and therefore remains cold, which could lead to a CR source without a strong neutrino flux as well. This requires for both models, however, that in the vicinity of the source and in the presence of the strong electromagnetic field, the CR flux does not meet an interaction target with densities larger than of the order of $10^{-6}$ cm$^{-3}$. Linear acceleration in the polar and outer gaps is also possible but cannot explain the CR flux since losses are dominant (Zhang et al. 2003).

Finally, if CRs are mostly heavier nuclei, then muon acceleration is even more important. Since the CR energy is divided among many $A$ nucleons, the maximum neutrino energy is reduced to $0.08/A$ of the maximum CR energy, and so the neutrino flux at high energies is heavily suppressed. However, if the muons are significantly accelerated before they decay, then the maximum energy increases to 30%—a very large increase over $0.08/A$.

6. CONCLUSIONS

In conclusion, many of the proposed sites of CR acceleration are transient objects, which must have very high accelerating gradients if they are to produce UHE CRs. For gradients above $1.6$ keV cm$^{-1}$, muons will be accelerated significantly before they decay. When this happens, the neutrino flux is significantly enhanced, and the maximum neutrino energy increases. For photohadronic interactions, the maximum energy rises from about 8% of the primary proton energy up to about 30% of the maximum attainable energy. For matter dominated sources, this may be higher than the maximum proton energy.

Current IceCube diffuse neutrino flux limits have been used to set two-dimensional limits on accelerating gradient and source opacity or target density. When muon acceleration is considered, the IceCube limits exclude several current models for UHE CR acceleration, such as plasma wave acceleration at different types of sources. The concept of stochastic acceleration is limited to an acceleration gradient of $<30$ keV cm$^{-1}$ per acceleration cycle in the case of GRBs and magnetar models can be excluded when the acceleration and interaction regions coincide. More generally, in any model of CR acceleration in compact sources, muon and pion acceleration must be included when the neutrino flux is considered.

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