COSMIC RAYS ABOVE THE SECOND KNEE FROM CLUSTERS OF GALAXIES AND ASSOCIATED HIGH-ENERGY NEUTRINO EMISSION

KOHTA MURASE,1 SUSUMU INOUE,2,3 AND SHIGEHIRO NAGATAKI1

Received 2008 July 31; accepted 2008 October 28; published 2008 November 20

ABSTRACT

Accretion and merger shocks in clusters of galaxies are potential accelerators of high-energy protons, which can give rise to high-energy neutrinos through pp interactions with the intracluster gas. We discuss the possibility that protons from cluster shocks make a significant contribution to the observed cosmic rays in the energy range between the second knee at \( \sim 10^{17.5} \) eV and the ankle at \( \sim 10^{18.5} \) eV. The accompanying cumulative neutrino background above \( \sim \)PeV may be detectable by upcoming neutrino telescopes such as IceCube or KM3NeT, providing a test of this scenario as well as a probe of cosmic-ray confinement properties in clusters.

Subject headings: acceleration of particles — cosmic rays — galaxies: clusters: general — neutrinos

Online material: color figure

1. INTRODUCTION

Clusters of galaxies (CGs) represent the largest gravitationally bound objects in the universe (e.g., Voit 2005). According to standard, hierarchical scenarios of cosmological structure formation, they are the latest systems to virialize and continue to grow through merging and accretion of dark matter and baryonic gas, thereby generating powerful shock waves on Mpc scales. In particular, accretion shocks with high Mach numbers are expected on the outskirts of massive CGs, potentially leading to efficient acceleration of high-energy particles (e.g., Miniaci et al. 2000; Ryu et al. 2003). Here “accretion” signifies not only infall of diffuse intergalactic gas, but also minor merger events that induce sufficiently strong shocks near the virial radii. Moderate Mach number shocks arising farther inside the CG could also be important in certain situations (e.g., Ryu et al. 2003). Predictions for the associated nonthermal radiation, notably high-energy gamma rays, have been discussed by a number of authors (e.g., Völk et al. 1996; Berezinsky et al. 1997; Colafrancesco & Blasi 1998; Loeb & Waxman 2000; Inoue et al. 2005; Ando & Nagai 2008).

Cosmic rays (CRs) are observed over 11 decades of energy from \( \sim 10^3 \) to \( \sim 10^{20} \) eV, and their origin is under intense debate. The all-particle spectrum is characterized by broken power laws with a number of breaks: the knee at \( \sim 10^{15.3} \) eV where the spectral index changes from \( \sim 2.7 \) to \( \sim 3.0 \), the second knee at \( \sim 10^{17.5} \) eV where it changes from \( \sim 3.0 \) to \( \sim 3.2 \), and the ankle at \( \sim 10^{18.5} \) eV where it changes from \( \sim 3.2 \) to \( \sim 2.7 \) (Nagano & Watson 2000). Galactic supernova remnants (SNRs) are widely believed to be responsible for CRs at least up to the knee, and probably up to somewhat higher energies (Hillas 2005 and references therein). In contrast, ultra-high-energy CRs (UHECRs) with energies above the ankle are generally thought to be extragalactic (e.g., Nagano & Watson 2000; Gaisser & Stanev 2005 and references therein). Inoue et al. 2005; Ando & Nagai 2008).

Cosmic rays (CRs) are observed over 11 decades of energy from \( \sim 10^3 \) to \( \sim 10^{20} \) eV, and their origin is under intense debate. The all-particle spectrum is characterized by broken power laws with a number of breaks: the knee at \( \sim 10^{15.3} \) eV where the spectral index changes from \( \sim 2.7 \) to \( \sim 3.0 \), the second knee at \( \sim 10^{17.5} \) eV where it changes from \( \sim 3.0 \) to \( \sim 3.2 \), and the ankle at \( \sim 10^{18.5} \) eV where it changes from \( \sim 3.2 \) to \( \sim 2.7 \) (Nagano & Watson 2000). Galactic supernova remnants (SNRs) are widely believed to be responsible for CRs at least up to the knee, and probably up to somewhat higher energies (Hillas 2005 and references therein). In contrast, ultra-high-energy CRs (UHECRs) with energies above the ankle are generally thought to be extragalactic (e.g., Nagano & Watson 2000; Gaisser & Stanev 2005 and references therein). Inoue et al. 2005; Ando & Nagai 2008).

1 YITP, Kyoto University, Kyoto, Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto 606-8502, Japan; kmurase@yukawa.kyoto-u.ac.jp.

2 Division of Theoretical Astronomy, National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan.

3 Department of Physics, Kyoto University, Kyoto, Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto 606-8502, Japan.

2. COSMIC-RAY PRODUCTION

We first estimate the maximum energy of the accelerated CRs. The virial radius of a CG with mass \( M = 10^{15} M_\odot \) is \( r_{\text{vir}} \approx 2.4 \) Mpc \( M_\odot^{-1/3} F(z, \Omega_m) (h/0.7)^{-1} (1+z)^{-1} \), where \( F(z, \Omega_m) \) is a factor of order unity that depends weakly on redshift \( z \) and \( \Omega_m \) (Voit 2005). We write the shock radius as \( r_{sh} \approx \lambda_{sh} r_{\text{vir}} \), with \( \lambda_{sh} \sim 1–10 \) expected for accretion shocks (e.g., Ryu et al. 2003). The typical shock acceleration time for CRs with energy \( E \) is \( t_{\text{acc}} \approx 20 \kappa_{sh} V_{sh}^2 / (20/3) (\text{cev}/Z_{f}B_{f})^{2} \) (Inoue et al. 2005).

The typical shock acceleration time for CRs with energy \( E \) and charge \( Z \) is \( t_{\text{acc}} \approx 20 \kappa_{sh} V_{sh}^2 / (20/3) (\text{cev}/Z_{f}B_{f})^{2} \) (Inoue et al. 2005). See, e.g., Blandford & Eichler 1987 for reviews). Here \( B \) and \( \kappa_{sh} \) are respectively the magnetic field and diffusion coefficient at the shock, and \( \xi = (B/\delta B)^2 \) where \( \delta \rightarrow 1 \) in the Bohm limit. Although the magnetic fields at cluster shocks are uncertain, we take \( B \approx 1 \) \( \mu \text{G} \), as supported by recent X-ray observations of diffuse radio relics near \( r_{\text{vir}} \) for several CGs (Feretti & Neummann 2006; Chen et al. 2008; Nakazawa et al. 2008). We also postulate \( \xi \approx 1 \), as observed to be the case for some SNRs...
The maximum energy of the accelerated CRs $E_{\text{max}}$ can be estimated by equating $t_{\text{acc}}$ with various limiting timescales, such as the diffusive escape time from the shock $t_{\text{esc}} \approx r_{\text{sh}}/\Delta v_{\text{sh}}$ and the energy loss time due to photodisintegration interactions with the CMB and the infrared (IR) background (Kang et al. 1997; Inoue et al. 2007). When the shock is due to a transient merger-like event, the lifetime of the shock may also be relevant, which can be calculated by the dynamical time $t_{\text{dyn}} = r_{\text{sh}}/V_{\text{sh}}$. In the latter case, $E_{\text{max}}$ would generally be determined by $t_{\text{dyn}}$ so that $E_{\text{max}} \approx 1.6 \times 10^{18}$ eV $\times Z_{\odot}^{-1/2} M_{\odot}^{1/2} B_{-6}^{2/3}$, where $B = B_{-6}$ [G]. Hence, we expect that cluster shocks can accelerate at least protons up to around the ankle (Norman et al. 1995).

Next we consider the energetics. Assuming a total mass accretion rate $M \approx 0.1V_{\odot}/G$ and gas fraction $f = \Omega_{\text{gas}}/\Omega_{\text{tot}} \sim 0.13$, the dissipation rate of infalling gas kinetic energy through the accretion shock of a CG with mass $M$ is estimated to be $L_{\text{acc}} \approx f_{\gamma} GM M_{\odot}/c_{\text{sh}} \approx 7 \times 10^{48}$ erg s$^{-1}$ ($f_{\gamma}$/0.13)$M_{\odot}$ (Keshet et al. 2004). Taking the local density of massive CGs $n_{\text{CG}} (M \geq M_{\odot}) \sim 2 \times 10^{-6}$ Mpc$^{-3}$ (Jenkins et al. 2001) and a CR injection efficiency $\epsilon_{\text{acc}} = 0.2$, the CR power from CGs per logarithmic energy interval at $\epsilon = 10^{18}$ eV is $E_{\text{CR}} (dN/d\epsilon) \sim 10^{45}$ erg Mpc$^{-3}$ yr$^{-1}$ ($R/500$)$^{-1}$. Here $R(\epsilon) \equiv [E_{\text{max}} (\text{de})/E_{\text{d}} (\text{dN}/d\epsilon)]/[E_{\text{d}} (\text{dN}/d\epsilon)]$ depends on the injection CR spectrum; in the case of a single power-law with index $p$ and minimum energy $E_{\text{min}} = 1$ GeV, $R \sim 25$ for $p = 2.0$, and $R \sim 300$ for $p = 2.2$ (Murase et al. 2008).

In comparison, the observed CR spectrum for $10^{17} < \epsilon < 10^{18.5}$ eV is $\Phi /E^{-3.2}$ (Nagano & Watson 2000). The implied CR source18 $p_{\text{min}} \approx 1.8 \times 10^{17}$ eV $Z_{\odot}/(r_{\text{sh}}/1$ Gyr)$^{-1}$, where $k_{\text{SG}} = 10^{9} k_{\text{CG}, 30}$ cm$^{-2}$ s$^{-1}$ is the diffusion coefficient in the ICM at $\epsilon = 1$ GeV, and $\Delta t$ is the time elapsed after injection (Völk et al. 1996; Berezhnyski et al. 1997). Within the uncertainties, we see that CGs could be a viable source of CRs with energies between the second knee and the ankle.

3. NEUTRINO PRODUCTION

We now evaluate the spectra of associated gamma rays and neutrinos, which are inevitably generated through $pp$ interactions with the ambient ICM gas (Völk et al. 1996; Berezhnyski et al. 1997; Colafrancesco & Blasi 1998). In view of the above, we assume that CRs with a broken power-law spectrum is realized with $p_{1} = 2.0$ and $p_{2} = 2.4$. We choose $\epsilon_{b} = 10^{16.5}$ eV or $10^{17.5}$ eV, giving respectively $R \approx 78$ or 35. The spatial distribution of the thermal ICM gas is generally well constrained from X-ray observations (Pfrommer & Enßlin 2004). However, for the CRs is uncertain, and we consider the following four models. (1) Model A: CRs are uniformly distributed within $r_{\text{sh}}$ with $\Delta v_{\text{sh}}$ chosen such that $t_{\text{dyn}} = 1$ Gyr. (2) Model B: CRs are uniformly distributed within $r_{\text{sh}}$, giving a conservative estimate compared to other models. (3) Isobaric model: CRs at each radii have energy density proportional to that of the thermal gas with ratio $X_{\text{CR}}$ (Pfrommer & Enßlin 2004; Ando & Nagai 2008). (4) Central AGN model: CRs are distributed as $dN/d\epsilon \propto \epsilon^{-2}$ for $\epsilon \geq (r_{\text{sh}}/6k_{\text{CG}, 30}^{-1})^{1/3}$ and

Another possibility is a two-step acceleration process, a first source providing a seed CR population with hard spectra ($p_{1} \sim 2.0$) up to $\epsilon_{b}$, which is then picked up by a second source and accelerated further with softer spectra to $E_{\text{max}}$. Since CRs with sufficiently low energies are likely to be confined in the intracluster medium (ICM) for very long times (Völk et al. 1996; Berezhnyski et al. 1997) the seed population can come from a number of sources, all accumulated over the history of the CG: the low-energy portion of accretion shock CRs, supernova-driven galactic winds (GWs), and the jets of radioloud active galactic nuclei (AGNs). Their relative importance can be estimated through their contributions to the heating of the ICM, which should be roughly proportional to their CR output as long as the relevant shocks are sufficiently strong. In the absence of GWs or AGNs, high Mach number accretion shocks are expected to contribute $\sim 10\%$ of the heating of the ICM, while the remainder is mediated by low Mach number merger shocks (e.g., Ryu et al. 2003). GWs are unlikely to play a significant role in ICM heating due to severe radiative losses during their formation (e.g., Kravtsov & Yepes 2000). (Note that CRs of supernova origin escaping from within the host galaxy will also suffer heavy adiabatic losses). In contrast, AGN jets can contribute $1–2$ keV per baryon of heat input directly to the ICM (Inoue & Sasaki 2001) (see also Enßlin et al. 1997, 1998). For massive clusters with temperatures $\sim 10$ keV, this implies that CRs from AGNs can be energetically comparable to those from accretion shocks, and may be even higher for less massive clusters. Subsequent acceleration of these seed CRs to $E_{\text{max}}$ may be achieved through merger and/or accretion shocks with moderate Mach numbers $M \sim 2.5–5$, leading to $p_{2} \sim 2.2–2.7$. The break energy $\epsilon_{b}$ may correspond to the confinement energy $E_{\text{conf}}$ above which CRs begin to escape diffusively out of the ICM. Under Kolmogorov-like turbulence, $E_{\text{conf}} \approx 1.8 \times 10^{17}$ eV $Z_{\odot}/(r_{\text{sh}}/1$ Gyr)$^{-1}$, where $k_{\text{SG}} = 10^{9} k_{\text{CG}, 30}$ cm$^{-2}$ s$^{-1}$ is the diffusion coefficient in the ICM at $\epsilon = 1$ GeV, and $\Delta t$ is the time elapsed after injection (Völk et al. 1996; Berezhnyski et al. 1997). Within the uncertainties, we see that CGs could be a viable source of CRs with energies between the second knee and the ankle.

We consider two possibilities as to how such spectra may actually occur. One is through the superposition of hard spectra ($p_{1} \sim 2.0$) with a distribution of $E_{\text{max}}$ (Kachelrieß & Semikoz 2006) which can be related to accretion shocks with a distribution of $M$. It was seen that $E_{\text{max}} \propto M^{-2/3}$ if the relevant condition is $t_{\text{esc}} \approx t_{\text{dyn}}$ and if the $M$-dependence of $B$ is not strong. A realistic CG mass function $n_{\text{CG}} (M) \propto M^{-1}$ exp $[-(M/1.8 \times 10^{14} M_{\odot})]$ can be approximated over a limited range of $M$ as a power law $n_{\text{CG}} (M) \propto M^{-\alpha}$ (Jenkins et al. 2001) so that $dN/d\epsilon \propto E^{-3\alpha/2-1/3}$ for $\epsilon > \epsilon_{b}$. This could allow $p_{1} \sim 2.0$ and $p_{2} \sim 2.0–3.3$.

Another possibility is a two-step acceleration process, a first source providing a seed CR population with hard spectra
The neutrino and gamma-ray fluxes can be estimated via the effective optical depth for the pp reaction as \( f_{pp} \approx 0.8 \sigma_{pp} n_n c \tau_{int} \), where \( n_n \) is the target nucleon density in the ICM, \( \sigma_{pp} \) is the pp cross section, and \( t_{int} \sim t_{pp} \) or \( \max(\nu/c, t_{up}) \) is the pp interaction time. Because \( n_n \sim 10^{-4.5} \text{ cm}^{-3} \) at \( r \sim 1.5 \text{ Mpc} \) (Colafrancesco & Blasi 1998; Pfrommer & Enßlin 2004), \( \kappa_{pp} \sim 0.6 \), and \( \sigma_{pp} \sim 10^{-23} \text{ cm}^2 \) in the 100 PeV range (Kelner et al. 2006), we obtain

\[
f_{pp} \approx 2.4 \times 10^{-3} n_{N_\bullet} (t_{up}/1 \text{ Gyr}).
\]

Roughly speaking, high-energy neutrinos from charged-pion decay have typical energy \( \epsilon_\nu \sim 0.03 \epsilon \) (true only in the average sense, because charged particles have wide energy distributions and high multiplicities as expected from the KNO scaling law) (Kelner et al. 2006). Hence, neutrinos \( \gtrsim \text{PeV} \) are directly related to CRs above the second knee.

First we obtain numerically the neutrino spectra and expected event rates from five nearby CGs, utilizing the \( \beta \) model or double-\( \beta \) model description in Tables 1 and 2 in Pfrommer & Enßlin (2004) for the thermal gas profile of each CG (Fig. 1).

Our gamma-ray fluxes for single power-law spectra agree with the results of Pfrommer & Enßlin (2004). As is apparent in Figure 1, the detection of neutrino signals from individual CGs could be challenging even for nearby objects. It may be achievable, however, through a detailed stacking analysis.

More promising would be the cumulative background signal. A rough estimate of the neutrino background is (e.g., Murase 2007; Waxman & Bahcall 1998)

\[
e^2 \Phi_\nu \sim \frac{c}{4 \pi H_0} \frac{1}{3} \min(1, f_{pp}) e^2 \frac{dN}{dt} n_{CG}(0)f_c \sim 1.5 \times 10^{-9} \text{ GeV cm}^{-2} \text{ sr}^{-1} \text{s}^{-1} f_c
\]

\[
\times \frac{f_{pp}(\epsilon = 10^{18} \text{ eV})}{2.4 \times 10^{-3}} \left( \frac{\epsilon_\nu}{10 \text{ PeV}} \right)^{-2.1},
\]

where CGs are assumed to be the main sources of CRs from the second knee to the ankle. Here, \( n_{CG}(0) \) is the local density of massive CGs and \( f_c \) is a correction factor for the source evolution (Murase 2007; Waxman & Bahcall 1998). For detailed numerical calculations of the background, we treat more distant CGs following Colafrancesco & Blasi (1998) adopting the mass function of Jenkins et al. (2001). The results for the broken power-law case are shown in Figure 2. With \( \epsilon_\nu \sim 10^{17.5} \text{ eV} \), the expected event rates above 0.1 PeV in IceCube (Ahrens et al. 2004) are \( \sim 2 \text{ yr}^{-1} \) for model A, \( \sim 1 \text{ yr}^{-1} \) for model B, \( \sim 5 \text{ yr}^{-1} \) for the isotropic model, and \( \sim 3 \text{ yr}^{-1} \) for the central AGN model.

Hence, upcoming telescopes may be able to find multi-PeV neutrino signals from CGs, providing a crucial test of our scenario. From equation (2), we can also estimate the corresponding gamma-ray background from \( \pi^0 \) decay, which is \( e^2 \Phi_{\gamma} \sim (10^{-9} \text{ to } 10^{-8}) \text{ GeV cm}^2 \text{ s}^{-1} \text{ sr}^{-1} \) for the broken power-law case. This is only (0.1–1)% of the EGRET limit, consistent with the nondetection so far for individual CGs. Note that the expected gamma-ray background flux would increase if \( \epsilon_\nu \) can be decreased, requiring larger CR power from CGs.

4. IMPLICATIONS AND DISCUSSION

To test the CG origin of second knee CRs, high-energy neutrinos should offer one of the most crucial multimeessenger signals. Unlike at the highest energies, CRs themselves in the \( 10^{18} \text{ eV} \) range offer no chance of source identification as they should be severely deflected by Galactic and extragalactic magnetic fields. Moreover, due to magnetic horizon effects, extragalactic CRs \( \lesssim 10^{17} \text{ eV} \) may not reach us at all (Lemoine 2005; Kotera & Lemoine 2007) so even the broken power-law spectral form will not be directly observable. Gamma-rays are unaffected by intervening magnetic fields, but those at \( \gtrsim \text{PeV} \) energies relevant for the second knee are significantly attenuated by pair-creation processes with the CMB and cosmic IR backgrounds (e.g., Kachelrieß 2008). In contrast, neutrinos in the PeV–EeV energy range should be unscathed during propagation (Bhattacharjee & Sigl 2000 and references there in). Con-
sequently, such neutrinos may also constitute a unique tool for probing the uncertain CR confinement properties of CGs through the dependence on $\epsilon_{\nu_{\mu}}$.

AGNs can complicate the cluster shock neutrino signal, either by emitting PeV–EeV neutrinos themselves, or injecting CRs that produce neutrinos without the intervention of cluster shocks. In principle, cross correlation of the detected events with known CGs and AGNs should be an effective discriminant. In the former case, AGNs inside as well as outside CGs should correlate, whereas in the latter, CGs with powerful AGNs should correlate stronger than those without. For cluster shock neutrinos, correlation with all sufficiently massive CGs is expected.

Gamma-ray observations at GeV–TeV energies would also be crucial. In combination with $\gtrsim$PeV neutrino observations, they can probe the CR spectrum over a broad energy range and test our broken power-law assumption. By providing information on the spatial distribution of sub-PeV CRs, they would also help to distinguish among our different models, and to constrain the AGN contribution of CRs and neutrinos. However, if $\epsilon_{\nu_{\mu}}$ is sufficiently high, their detection may not be trivial except for a few nearby CGs such as Virgo. Other emission processes may also be at work (e.g., Loeb & Waxman 2000; Inoue et al. 2005), complicating the extraction of the $\pi^0$ decay component. More details on the gamma-ray emission will be given in a following paper.

Note that high-energy neutrinos can also be produced by photomeson interactions with the IR background (e.g., Takami & Sasaki 2001; Inoue, Aharonian, & Sugiyama 2005), giving in a following paper.

We defer the study of such photomeson-induced neutrinos in CGs to the future.

K. M. and S. I. thank T. Kitayama, R. Blandford, F. Takahara, and H. Takami for useful comments. K. M. is supported by a JSPS fellowship. S. I. is supported in part by Grants-in-Aid for Scientific Research from the Ministry of E.C.S.S.T. (MEXT) of Japan, Nos. 19047004 and 19540283. S. N. is likewise partially supported by Nos. 19104006, 19740139, and 19047004. Support also comes from the Grant-in-Aid for the Global COE Program “The Next Generation of Physics, Spun from Unversality and Emergence” from MEXT.

**REFERENCES**

Abbasi, R. U., et al. 2008, preprint (arXiv:0804.0382)
Abraham, J. C., et al. 2007, Science, 318, 938
Ahrens, J., et al. 2004, Astropart. Phys., 20, 507
Aloisio, R., et al. 2007, Astropart. Phys., 27, 76
Ando, S., & Nagai, D. 2008, MNARS, 385, 2243
Bell, A. R. 2004, MNARS, 353, 550
Bell, A. R., & Lucek, S. G. 2001, MNARS, 321, 433
Berezhyns’kyi, V. S., Blasi, P., & Ptuskin, V. S. 1997, ApJ, 487, 529
Berezhnyi, V. S., Gazzlovri, A. Z., & Grigorieva, S. I. 2006, Phys. Rev. D, 74, 043005
Bergman, D. R., & Belz, J. W. 2007, J. Phys. G, 34, R359
Bhattacharjee, P., & Sigl, G. 2000, Phys. Rep., 327, 109
Blandford, R. D., & Eichler, D. 1987, Phys. Rep., 154, 1
Budnik, R., Katz, B., MacFadyen, A., & Waxman, E. 2008, ApJ, 673, 928
Bykov, A. M., Dolag, K., & Durret, F. 2008, Space Sci. Rev., 134, 119
Bykov, A. M., et al. 2006, Space Sci. Rev., 134, 119
Chen, C. M. H., et al. 2008, ApJ, 628, L9
Chen, C. M. H., et al. 2006, Phys. Rev. D, 74, 043004
Enßlin, T. A., Biermann, P. L., Kronberg, P. P., & Blasi, P. 2006, Phys. Rev. D, 73, 043004
Enßlin, T. A., et al. 2008, preprint (arXiv:0804.0382)
Ferretti, L., & Neumann, D. M. 2006, A&A, 450, L21
Gaisser, T. K., & Stanev, T. 1997, Nucl. Phys. A, 777, 98
Gaisser, T. K., & Stanev, T. 2006, Nucl. Phys. A, 777, 98
Hillas, A. M. 2005, J. Phys. G, 31, R95
Inoue, S. 2008, J. Phys. Conf. Ser., 120, 062001 (arXiv:0809.3205)
Inoue, S., Aharonian, F. A., & Sugiyama, N. 2005, ApJ, 628, L9
Inoue, S., & Sasaki, S. 2001, ApJ, 562, 618
Inoue, S., Sigl, S., Miniati, F., & Armengaud, E. 2007, preprint (astro-ph/0701167)
Jenkins, A., et al. 2001, MNARS, 321, 372
Kachelriß, M. 2008, preprint (arXiv:0801.4376)
Kachelriß, M., & Semikoz, D. V. 2006, Phys. Lett. B, 634, 143
Kang, H., Rachen, J. P., & Biermann, P. L. 1997, MNARS, 286, 257
Kang, H., Ryu, D., & Jones, T. W. 1996, ApJ, 456, 422
Katz, U. F. 2006, Nucl. Instrum. Methods Phys. Res. A, 567, 457
Kelner, S. A., Aharonian, F. A., & Bugayov, V. Y. 2006, Phys. Rev. D, 74, 034018
Keshet, U., Waxman, E., & Loeb, A. 2004, ApJ, 617, 281
Kotera, K., & Lemoine, M. 2007, Phys. Rev. D, 77, 023005
Kravtsov, A. V., & Yepes, G. 2000, MNARS, 318, 227
Lemoine, M. 2005, Phys. Rev. D, 71, 083007
Loeb, A., & Waxman, E. 2000, Nature, 405, 156
Miniati, F., et al. 2000, ApJ, 542, 608
Murase, K. 2007, Phys. Rev. D, 76, 123001
Murase, K., Ioka, K., Nagataki, S., & Nakamura, T. 2008, Phys. Rev. D, 78, 023005
Nagano, N., & Watson, A. A. 2000, Rev. Mod. Phys., 72, 689
Nakazawa, K., et al. 2008, PASJ, submitted
Norman, C. A., Melrose, D. B., & Achterberg, A. 1995, ApJ, 454, 60
Pfrommer, C., & Enßlin, T. A. 2004, A&A, 413, 17
Ryu, D., et al. 2003, ApJ, 593, 599
Takami, H., Murase, K., Nagataki, S., & Sato, K. 2007, preprint (arXiv:0704.0979)
Uchiyama, Y., et al. 2007, Nature, 449, 576
Vladimirov, A., Ellison, D. C., & Bykov, A. 2006, ApJ, 652, 1246
Voit, G. M. 2005, Rev. Mod. Phys., 77, 207
Vol’k, H. J., Aharonian, F. A., & Breitschwerdt, D. 1996, Space Sci. Rev., 75, 279
Wang, X. Y., et al. 2003, ApJ, 593, 599
Waxman, E., & Bahcall, J. 1998, Phys. Rev. D, 59, 023002