GAMMA RAYS FROM ULTRA-HIGH-ENERGY COSMIC RAYS IN CYGNUS A

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ABSTRACT

Ultra-high-energy cosmic rays (UHECRs) accelerated in the jets of active galactic nuclei can accumulate in high magnetic field, $\sim$100 kpc–scale regions surrounding powerful radio galaxies. Photohadronic processes involving UHECRs and photons of the extragalactic background light make ultrarelativistic electrons and positrons that initiate electromagnetic cascades, leading to the production of a $\gamma$-ray synchrotron halo. We calculate the halo emission in the case of Cygnus A and show that it should be detectable with the Fermi Gamma-Ray Space Telescope and possibly detectable with ground-based $\gamma$-ray telescopes if radio galaxies are the sources of UHECRs.

Subject headings: galaxies: active — galaxies: individual (Cygnus A) — galaxies: jets — gamma rays: theory — radiation mechanisms: nonthermal

1. INTRODUCTION

Active galactic nuclei (AGNs) and gamma-ray bursts are considered as two of the most plausible classes of astrophysical accelerators of extragalactic ultra-high-energy cosmic rays (UHECRs; see, e.g., Halzen & Hooper 2002). The recent report of the Pierre Auger Collaboration (Abraham et al. 2007) about clustering of the arrival directions of UHECRs with energies $E \approx 6 \times 10^{19}$ eV within $\approx 3^\circ$ of the directions to AGNs at distances $d \approx 75$ Mpc strongly suggests that effective production of cosmic rays with energies $E \approx 10^{20}$ eV takes place in at least one of these source classes. Because of photohadronic GZK (Greisen-Zatsepin-Kuzmin) interactions of protons or ions with the CMB radiation, the study of super-GZK UHECRs from sources at $d \approx 100$ Mpc becomes impossible with cosmic-ray detectors like the Pierre Auger Observatory (Harari et al. 2006). Powerful AGNs, as well as GRBs, are mostly located at larger distances.

Relativistic beams of energy from the central nuclei of AGNs are thought to power the multi-kpc-scale radio lobes of powerful galaxies and form an extended cavity (Scheuer 1974). Acceleration of UHECRs in the compact inner jets of the radio galaxy on the subparsec scale, followed by production of collimated beams of ultra-high-energy neutrons and gamma rays, provides a specific mechanism to transport energy to the radio lobes and cavity (Atoyan & Dermer 2003). When the neutron-decay UHECR protons interact with the extragalactic background light (EBL), which is dominated by the CMB radiation, decay UHECR protons interact with the extragalactic backlobe and cavity (Atoyan & Dermer 2003). When the neutron-decay UHECR protons interact with the extragalactic background light (EBL), which is dominated by the CMB radiation, decay UHECR protons interact with the extragalactic backlobe and cavity (Atoyan & Dermer 2003). When the neutron-decay UHECR protons interact with the extragalactic background light (EBL), which is dominated by the CMB radiation, decay UHECR protons interact with the extragalactic backlobe and cavity (Atoyan & Dermer 2003). When the neutron-decay UHECR protons interact with the extragalactic background light (EBL), which is dominated by the CMB radiation, decay UHECR protons interact with the extragalactic backlobe and cavity (Atoyan & Dermer 2003). When the neutron-decay UHECR protons interact with the extragalactic background light (EBL), which is dominated by the CMB radiation, decay UHECR protons interact with the extragalactic backlobe and cavity (Atoyan & Dermer 2003).

2. MODEL PARAMETERS

Magnetic fields $B \approx 1 \mu$G could be present at $\lesssim 1$ Mpc scales in clusters of galaxies (Kim et al. 1990; Feretti et al. 1995; Ferrari et al. 2008). Even higher magnetic fields, $B \approx 10^{-4}$ G, could be present in the $r \approx 100$ kpc vicinity of cD galaxies near the center of galaxy clusters like the powerful radio galaxy Cyg A (Wilson et al. 2006). In such magnetic fields, synchrotron radiation of electrons with $E \approx 10^{19}$ eV produced in photomeson interactions is in the TeV domain. Furthermore, synchrotron radiation of lower energy electrons produced in $p + \gamma \rightarrow p + e^+ + e^-$ interactions by UHECRs extends to the GeV domain and could become detectable with Fermi. Here we consider the detectability of these fluxes from the powerful and well-studied radio galaxy Cyg A.

2.1. Power of the Cosmic-Ray Accelerator

Observations of Cygnus A ($z = 0.056$, luminosity distance $\sim 240$ Mpc) by the Chandra X-Ray Observatory show that the central $\sim 60$ kpc $\times$ 120 kpc size luminous prolate spheroidal region of Cygnus A, called a “cavity,” can be understood as a shock expanding into the accretion cooling-flow gas (Wilson et al. 2006). The kinetic power of expansion of this X-ray cavity deduced by Wilson et al. (2006) is $L_{\text{kin}} \approx 1.2 \times 10^{46}$ erg s$^{-1}$. This is much larger than the total radio luminosity $L_{\text{radio}} \approx 10^{43}$ erg s$^{-1}$ of the two bright radio lobes of Cygnus A (Perley et al. 1984). The value of $L_{\text{exp}}$ should be considered as a lower limit to the overall power $L_{\text{CR}}$ of cosmic rays injected into the cavity, if the cosmic-ray power is assumed to drive the expansion of the cavity. A few times larger power, $L_{\text{CR}} \sim 4 \times 10^{46}$ erg s$^{-1}$, therefore seems a reasonable assumption.

This value is in a good agreement with the “neutral beam” model (Atoyan & Dermer 2001, 2003), which explains the collimated relativistic X-ray jets that remain straight up to $\approx 1$ Mpc distances in sources such as Pictor A (Wilson et al. 2001).
as the result of energy transport by beams of UHE neutrons and gamma rays. These linear X-ray features, surrounded by a broader and less collimated radio structure in Pictor A, and coincident with narrow radio structures exhibiting bends and deflections in Cyg A (Carilli et al. 1996; Steenbrugge & Blundell 2008), terminate in X-ray hot spots. Because of the large inclination angle, the X-ray jets in Cyg A cannot be detected. However, detection of bright X-ray hot spots located at 60 kpc distances on opposite sides of the nucleus (Wilson et al. 2006) strongly implies production of collimated X-ray jets also in Cyg A.

Detailed calculations in the framework of this model show that neutral beams of ultrarelativistic neutrons and γ-rays, produced by the compact relativistic jets in the central subparsec-scale environment of FR II galaxies, can take a few percent of the total power of this inner jet. That energy is then deposited, after β-decay of neutrons n → p + e + γ, on distance scales \( l_p \approx E_{20} \) Mpc, and also via photopair production of UHE gamma rays through the process \( γ + γ → e^+ + e^- \). These secondary charged relativistic particles initially form a beam in the same direction as the jet, and can effectively interact with and transfer momentum and energy to the ambient magnetized medium, and thus can be the basic energy reservoir for the jet at large distances from Cyg A. The total radio luminosity \( ≈ 9 \times 10^{44} \) erg s\(^{-1}\) detected from the lobes of Cyg A (Carilli & Barthel 1996; Wilson et al. 2006) imposes the minimum power requirement for the beam. Given the \((2−3)%\) efficiency of neutral beam production, the acceleration power of the CRs in the relativistic inner jet must be \( L_{\text{CR}} \approx (3−5) \times 10^{46} \) erg s\(^{-1}\). This power is then released in CRs when the inner jet decelerates to subrelativistic speeds in the dense medium at kpc scales. This scenario is in agreement with the assumption that the expansion of the cavity against the cooling flow observed (Smith et al. 2002) at distances 70–100 kpc is powered by cosmic-ray pressure.

Protons can be accelerated in the powerful inner jets of radio galaxies to a maximum energy \( E_{\text{max}} \approx 10^{50} \) eV, consistent with size scales and magnetic fields inferred from a synchrotron model of blazars corresponding to Cyg A if observed along its jet. This value of \( E_{\text{max}} \) is in accord with the distance of the hot spot where the large-scale jet terminates due to the β-decay of the remaining high-energy neutrons in the beam. At this distance, the injection power from the decaying neutrons is balanced by the ram pressure of the external medium. Thus, for \( l_p \approx 100 \) kpc–long jets originating from neutral beams, the inner jets must accelerate protons to \( E \approx 10^{19} \) eV. In our model, we assume that acceleration of UHECRs to \( E \approx 10^{20} \) eV occurs.

2.2. Magnetic Field Strength

The lower limit to the equipartition magnetic field in the radio lobes of Cyg A inferred from radio observations is \( ≈ 60 \) \( \mu \)G (Carilli et al. 1991). The equipartition magnetic field in the cavity derived from X-ray observations is \( B \approx 120 \) \( \mu \)G (Wilson et al. 2006). Moreover, the field outside the cavity could also be very high given the large thermal electron energy density inferred from the X-ray emission at \( ≲ 8' \), which corresponds to \( ≲ 500 \) kpc environment around Cyg A. The pressure of hot thermal gas decreases from 2.3 \( \times 10^{-16} \) erg cm\(^{-3}\) in the regions near the cavity to \( ≲ 10^{-11} \) erg cm\(^{-3}\) at distances \( ≲ 500 \) kpc from the center of Cyg A (Smith et al. 2002). The corresponding equipartition magnetic fields would then vary from \( \sim 80 \) to \( \sim 15 \) \( \mu \)G at the periphery of this region.

2.3. Injection Age

The duration of injection of UHECRs, i.e., the jet injection age, represents one of the important parameters of the model. Wilson et al. (2006) find that the expansion age of the cavity, determined from the speed of the shock deduced from the analysis of X-ray data, is \( t \approx 3 \times 10^7 \) yr. The injection age can be larger than this dynamical age because the derived value neglects the magnetic-field pressure of the intracluster medium (ICM) upstream of the shock, as recognized by Wilson et al. (2006). Also, this age estimate neglects the infall velocity of the cooling flow. For the total mass \( M \approx 2 \times 10^{13} M_\odot \) enclosed at \( r \lesssim 50 \) kpc distances (Smith et al. 2002), the virial speed \( v_{\text{vir}} \approx c / \sqrt{r/M} \approx 2000 \) km s\(^{-1}\), where \( v_g = 2GM/c^2 \approx 6 \times 10^{18} \) cm s\(^{-1}\) is, formally, the Schwarzschild radius for the total mass \( M \).

The value of \( v_{\text{vir}} \) gives a measure of the accretion/cooling flow velocities at radius \( r \), and is comparable to the average \( \sim 1500 \) km s\(^{-1}\) speed of the shock derived by Wilson et al. (2006) in the rest frame of the fluid upstream of the shock. These factors can significantly decrease the speed of expansion of the cavity in the stationary frame, so that the real injection age of the cavity can be significantly larger than the age inferred by Wilson et al. (2006).

We now estimate the age of activity of the black-hole jet from energetics arguments. The inferred jet power, \( L_{\text{jet}} \approx 4 \times 10^{49} \) erg s\(^{-1}\), corresponds to \( ≈ 12% \) of the Eddington luminosity for a black-hole mass \( M_{\text{BH}} \approx 2.5 \times 10^9 M_\odot \) in Cygnus A (Tadhunter et al. 2003). To produce such power, the black hole should accrete mass at the rate \( \dot{M} = L_{\text{jet}} / c^2 \approx (7/1) M_\odot \) yr\(^{-1}\) with an efficiency \( \eta = 10^{-1} \), with \( \eta_1 \approx 1 \). The age of the central black hole is estimated by its growth time \( t = M_{\text{BH}} / \dot{M} \approx 3.6 \times 10^9 \) yr, giving an upper estimate for the jet’s age as the jet might be active for only a fraction of the BH growth phase. These estimates are in accord with the characteristic jet age \( t \approx 10^8 \) yr inferred from a model for "cocoon" (or cavity) dynamics by Begelman & Cioffi (1989).

2.4. Cosmic-Ray Diffusive Confinement Time

The maximum confinement timescale \( t_{\text{conf}} \) of UHECRs in a source of size \( r \) is given in the Bohm diffusion approximation by \( t_{\text{conf}} \approx r^2 / 2D_B \), where the Bohm diffusion coefficient \( D_B = cr_3 / 3 \), and \( r_3 = E/QB \) is the Larmor radius of a particle with charge \( Q \). From this expression we obtain the UHECR proton confinement time

\[
t_{\text{conf}} \approx 0.95 \times 10^7 (r/100 \text{ kpc})^2 (E/20 \mu \text{G}) \text{ yr.} \tag{1}
\]

For \( r \approx 50 \) kpc and \( B \approx 120 \) \( \mu \)G, \( t_{\text{conf}} \approx 15 \) Myr for \( \approx 10^{20} \) eV protons.

Figure 1 compares timescales \( t_{\text{conf}} \) for energy losses due to photomeson and photopair production with values of \( t_{\text{conf}} \) for characteristic parameters \( r = 500 \) kpc and \( B = 20 \) \( \mu \)G in the region surrounding Cyg A. Also shown is the value of \( t_{\text{age}} = 10^8 \) yr for the assumed injection age. The fraction of energy of accelerated protons that could be extracted is given by \( \Lambda(E) = \min \left( t_{\text{conf}}, t_{\text{max}}, t_{\text{max}} \right) / t_{\text{max}} \). This figure shows that \( \approx 3\% \) of the total energy of UHECRs with \( E \approx 3 \times 10^{18} \) eV can be extracted through photopair processes. Because of the increased confinement time and the much lower production threshold for photopair than photomeson processes, the photopair process can make a comparable or dominant contribution to the electromagnetic channel compared to photomeson processes.
3. RESULTS

Figure 2 shows $\gamma$-ray fluxes calculated for the electromagnetic cascade initiated by the injection of $4 \times 10^{46}$ erg s$^{-1}$ of UHECR protons into the cavity, and further cosmic-ray interactions with the EBL in the $r=0.5$ Mpc region surrounding Cyg A. Even though the EBL is dominated by the CMBR, interactions with the diffuse infrared/optical radiation are also included in the calculations, using the EBL of Primack et al. (2005). The injection spectrum of UHECR protons is a power law with an $\alpha_p = -2.1$ number spectral index with a low-energy cutoff at $E = 1$ TeV and a high-energy exponential cutoff at $E = 3 \times 10^{20}$ eV. We assume a mean magnetic field $B = 20 \mu G$. Escape of particles is given by the Bohm diffusion approximation in a single-zone model. The method of calculation follows the approach described by Atoyan & Dermer (2003).

The solid, dashed, and dot-dashed curves in Figure 2 show the contributions to the fluxes from the photohadronic secondary electrons and the first two generations of cascade electrons for injection ages $t_{\text{age}} = 10^8$ yr. The secondary electrons also include the electrons from $\pi^0$-decay $\gamma$-rays that convert promptly into electron-positron pairs inside the source. In the strong magnetic field of the Cyg A environment, the Compton flux is dominated by synchrotron radiation from the photohadronic secondaries and the first generation of cascade electrons.

The open dots, filled dots, and stars in Figure 2 show the expected $E \times F(E)$ spectral energy fluxes for injection ages $t_{\text{age}} = 30, 100,$ and $300$ Myr, respectively. The lower and higher energy peaks in the spectral energy distributions primarily result from photopair and photomeson processes, respectively. The sensitivities for a one-year, $5 \sigma$ detection of a point source with Fermi in the scanning mode, and for a $50$ hr, $5 \sigma$ detection with VERITAS are shown. The lower bound of the VERITAS sensitivity applies to a point source, and the upper bound to a source of $25\%$ extent.

4. DISCUSSION AND CONCLUSIONS

If the radio lobes of Cyg A are powered by UHECR production from the inner pc-scale jets, then trapping of these particles in the surrounding strong magnetic-field region leads to the production of secondary $\gamma$-rays that should be significantly detected with Fermi in 1 year of observation if the jet injection age is $\geq 100$ Myr. If radio galaxies are not the sources of UHECRs, then Cygnus A will not be detected by Fermi. Cyg A could also be detected with VERITAS in a 50 hr pointing, depending on the duration of activity of the central engine and the level of the EBL.

Detection of GeV $\gamma$ rays from Cyg A with Fermi might also be expected to arise from other processes. The $\sim 10$–100 GeV radio-emitting electrons from the lobes of radio galaxies will Compton-scatter CMB photons to MeV–GeV energies (e.g., Cheung 2007). For the strong magnetic field, $\approx 60$ $\mu G$, in the lobes of Cyg A, however, the ratio of the magnetic-field to CMBR energy densities is $\approx 400$. Thus the total energy flux of Compton-scattered CMBR from Cyg A is $\approx 10^{46}$ erg s$^{-1}$, which is a factor of $\sim 5$ lower. As can be seen from Figure 2, this process is almost 2 orders of magnitude below the UHECR-induced synchrotron flux, and well below the Fermi sensitivity.

Inoue et al. (2005) considered fluxes expected from the $\approx 1$ Mpc halos of clusters of galaxies with weaker magnetic fields, $B = 0.1$–1 $\mu G$, in a model where acceleration of UHECRs occurs in accretion shocks in the cluster. Because of lower maximum energies of accelerated protons, $E \approx 10^{16}$ eV, and lower magnetic fields, this model predicts hard spectral fluxes of Compton origin peaking at TeV energies. Gabici & Aharonian (2005) predicted that synchrotron gamma radiation can be produced by...
secondaries of UHECRs that leave the acceleration region and travel nearly rectilinearly through weak intergalactic magnetic fields at the level $B \sim 10^{-7}$ to $10^{-9}$ G. These sources would appear as pointlike quiescent GeV–TeV sources with spectra in the GeV domain as hard as $\alpha \approx -1.5$, and very soft, $\alpha \approx -3$ spectra in the 100 GeV–TeV domain.

In contrast to both these models, we predict soft $0.1–1$ GeV spectra with and hard, spectra at TeV energies due to the much higher magnetic field in the confinement region. These models can be clearly distinguished if Cygnus A is resolved by the Fermi Gamma-Ray Space Telescope or the ground-based $\gamma$-ray telescopes, as the emission region in our model subtends an angle $\approx 10^\circ$.

Because Cygnus A lies outside the GZK horizon, only UHECRs with energy below the GZK energy could be correlated with this source. Other closer FR II radio galaxies that are correlated with the arrival directions of UHECRs are, however, candidate sources of $\gamma$-rays made through the mechanism proposed here. IGR J21247+5058 at $z = 0.02$ or $d \approx 80$ Mpc, recently discovered with INTEGRAL (Molina et al. 2007), is $2.1^\circ$ away from a HiRes Stereo event with $E > 56$ EeV (C. C. Cheung 2008, private communication). PKS 2158−380 at $\approx 140$ Mpc is also within $3.2^\circ$ degrees of an Auger UHECR with $E > 57$ EeV (Moskalenko et al. 2008). By comparison with Cyg A, these are low-luminosity FR IIs, and their predicted flux level will require detailed modeling for each source, as done here for Cyg A. Variability of $\gamma$-ray emission would rule out our model.

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