Constraining Sources of Ultra High Energy Cosmic Rays Using High Energy Observations with the Fermi Satellite

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We analyze the conditions that enable acceleration of particles to ultra-high energies, \(\sim 10^{20}\) eV (UHECRs). We show that broad band photon data recently provided by WMAP, ISOCAM, Swift and Fermi satellites, yield constraints on the ability of active galactic nuclei (AGN) to produce UHECRs. The high energy (MeV – GeV) photons are produced by Compton scattering of the emitted low energy photons and the cosmic microwave background or extra-galactic background light. The ratio of the luminosities at high and low photon energies can therefore be used as a probe of the physical conditions in the acceleration site. We find that existing data excludes core regions of nearby radio-loud AGN as possible acceleration sites of UHECR protons. However, we show that giant radio lobes are not excluded. We apply our method to Cen A, and show that acceleration of protons to \(\sim 10^{20}\) eV can only occur at distances \(\gtrsim 100\) kpc from the core.

The origin of ultra-high energy cosmic rays (UHECRs), with energies \(\gtrsim 10^{18.5}\) eV, is still under debate. Astrophysical sources of UHECRs are limited by two requirements: a strong magnetic field is needed to confine the accelerated cosmic rays, while the magnetic field cannot be too strong in order to avoid excessive synchrotron radiation and photo-meson energy losses. Several possible sources of UHECRs that fulfill these constraints are discussed in the literature. The leading candidates are gamma-ray bursts (GRBs), low luminosity gamma-ray bursts and hypernovae, and active galactic nuclei (AGNs).

The possibility that AGNs are the main source of UHECRs is challenged by the need for an unusually high photon luminosity. The required strong magnetic field, combined with the assumption that the energy density in the photon field is at least comparable to the energy density in the magnetic field, constrain the power output from the source to be \(L > 10^{45}\) \(\beta^{-4}\) erg s\(^{-1}\). Here, \(\Gamma\) and \(\beta c\) are the Lorentz factor and characteristic velocity within the source. Only very few AGNs within the GZK horizon fulfill this requirement. A detailed analysis of those AGNs whose position was found to be correlated with the arrival direction of UHECRs, resulted in a similar conclusion.

The underlying assumption of the above mentioned constraint is that the energy density in the photon field is comparable or higher than the energy density in the magnetic field. It is indeed difficult to obtain direct constraints on the value of the magnetic fields in AGNs and test this assumption.

In this paper, we re-analyze the constraints on AGNs as UHECR sources by combining low energy (radio-optical) and high energy (\(\sim\) MeV band) data, enabled by recent Swift and Fermi observatories. These data provide constraints on the magnetic field strength, and avoid the need to adopt the equipartition assumption. In addition, the broad band data itself places constraints on the allowed region within the AGN that can produce UHECRs. The constraints are based on observable quantities, and thus overcome the inherent uncertainty in estimating the magnetic field strength.

Basic requirements. Assuming that UHECRs acceleration results from electromagnetic processes within an expanding plasma, the requirement that the accelerated particles are confined to the acceleration region is equivalent to the requirement that the acceleration time, \(t_{\text{acc}} = \eta E_{\text{ob}}^2/(\Gamma Z e B c)\), is shorter than the dynamical time, \(t_{\text{dyn}} = r/\beta c\). This condition implies

\[
Br = \frac{\eta E_{\text{ob}}^2 \beta}{Ze} = 3.3 \times 10^{17} \beta \left(\frac{\eta E_{\text{ob}}^2}{20} \right) \text{G cm.} \tag{1}
\]

Here, \(E_{\text{ob}}\) is the observed energy of the particle, \(Ze\) is its charge, \(B\) is the magnetic field and \(r\) is the characteristic size of the acceleration region. \(\eta \geq 1\) is a dimensionless factor, whose exact value is determined by the uncertain details of the acceleration mechanism. Here and below, we use the convention \(Q = 10^X Q_X\) in cgs units.

A second condition is that the acceleration time is shorter than all relevant energy loss time scales. Energetic particles can lose their energy via synchrotron emission, on a time scale \(t_{\text{cool}} = (6\pi^2 m_e^3 c^2 \Gamma A^4)/(\sigma_T m_e^2 B^2 E_{\text{ob}}^2 Z^4)\). Here, \(\sigma_T\) is Thomson’s cross section, \(m_p\) and \(m_e\) are the proton and electron masses and \(A m_p\) is the mass of the nucleon (for iron nuclei, \(A = 56\) and \(Z = 26\)). The requirement \(t_{\text{acc}} < t_{\text{cool}}\) results in

\[
E_{\text{ob}} \lesssim 2 \times 10^{20} \frac{\Gamma}{\eta^{-1/2}} B^{-1/2} A^2 Z^{-3/2} \text{eV.} \tag{2}
\]
Thus, both protons and iron nuclei can be accelerated to the highest observed energies, $\sim 10^{20}$ eV, provided that the strength of the magnetic field at the acceleration site does not exceed $B \lesssim \text{few - few tens G}$.

In addition to synchrotron energy losses, energetic particles can in principle lose their energy by interacting with the ambient photon field and with other nuclei. Interaction with the photon field can result in energy losses by Compton scattering (which is typically a negligible energy loss channel for UHECRs), photopair production (Bethe-Heitler process), photo-production of mesons (mainly pions), and photodisintegration of heavy nuclei. Interaction with other nuclei can lead to spallation of heavy nuclei. These processes were studied in details for radio-loud AGNs in [22], and for radio-quiet AGNs in [23]. The results of both these works show that $\sim 10^{20}$ eV particles will survive all energy losses, provided that the acceleration site is located at $\sim$ few - few tens of parsecs from the core.

Assuming that electrons are being accelerated at the same acceleration site of the UHECRs, synchrotron emission is expected. Indeed, in many AGNs the peak of the synchrotron emission is clearly identified at the radio or infrared bands. The peak of the synchrotron energy flux can be approximated by assuming that the energetic electrons have a characteristic Lorentz factor $\gamma_e$.

\[
\nu_{\text{peak,syn}} = \frac{n_e V}{4\pi d_L^2} \left(\frac{4}{3}\right) c \sigma_T \gamma_e^2 \left(\frac{B^2}{8\pi}\right) D^2.
\]  

Here, $n_e$ is the number density of energetic electrons, $V$ is the volume of the emitting region, $d_L$ is the luminosity distance, $\sigma_T$ is the Thomson cross section and $D = [\Gamma(1 - \beta \cos(\theta^\text{obs}))]^{-1}$ is the Doppler factor for an observing angle $\theta^\text{obs}$ [57]. For an observer within the light cone, $\theta^\text{obs} < \text{max}(\Gamma^{-1}, \theta_{\text{jet}})$, $D \simeq \Gamma$, where $\theta_{\text{jet}}$ is the physical jet opening angle [58].

Recent Swift and Fermi observations revealed a second peak in the spectra of many AGNs, centered at $\sim$ MeV [e.g., 24, 26]. This second peak results from inverse-Compton (IC) scattering of low energy photons by the energetic electrons; a hadronic origin can be excluded by the lack of a neutrino counterpart [27]. Let us denote the flux ratio of the IC and the incoming photons peak energies by $\bar{R} = (\nu_{\text{F}_\nu})_{\text{peak,IC}} / (\nu_{\text{F}_\nu})_{\text{peak,inc}}$. We do not assume that the incoming photons are necessarily the synchrotron photons, and we thus denote their frequency by $\nu_{\text{in}}$, which can generally be different from $\nu_{\text{syn}}$. In an IC process, the outgoing photon energy is $\nu_{\text{out}} = (4/3)\gamma_e^2 \nu_{\text{in}}$, and the outgoing monochromatic (number) flux ratio of IC to synchrotron emission is $(F_{\nu})_{\text{peak,IC}} / (F_{\nu})_{\text{peak,inc}} = \tau \simeq \Delta ln\nu \sigma_T$. Approximating the volume of the acceleration region as cylindrical, $V = \pi r^2 \Delta l$, and substituting these results in equation (3), one obtains

\[
\nu_{\text{F}_\nu})_{\text{peak,syn}} = \frac{1}{4\pi d_L^2} \frac{c \bar{R} B^2 r^2}{8} D^2.
\]  

Combined with the constraint set in equation (1), one finds

\[
\nu_{\text{F}_\nu})_{\text{peak,syn}} \geq \frac{1}{4\pi d_L^2} \frac{c \bar{R}}{8} \left(\frac{\eta E_{\text{kin}}}{Z q}\right)^2 \beta^2 D^2.
\]  

\textbf{Emission from AGN cores.} A primary source of emission in AGNs is the core, or inner parts of the jet. Due to the high brightness temperature of the radio emission from this region, the seed photons to IC scattering are the synchrotron photons. Thus, $\bar{R} = (\nu_{\text{F}_\nu})_{\text{peak,IC}} / (\nu_{\text{F}_\nu})_{\text{peak,syn}} = Y$, where $Y = (4/3)\gamma_e^2 \tau$ is Compton parameter for an optical depth $\tau$. Equation (5) can be written as a constraint on the minimum synchrotron luminosity that is needed for a source to be able to produce UHECRs,

\[
L_{\text{peak,syn}} \equiv 4\pi d_L^2 (\nu_{\text{F}_\nu})_{\text{peak,syn}} \geq \frac{\gamma Y}{8} \left(\frac{\eta E_{\text{kin}}}{Z q}\right)^2 \beta^2 D^2
\]

\[
= 4.1 \times 10^{44} Y \left(\frac{\eta E_{\text{kin}}}{Z q}\right)^2 \beta^2 D^2 \text{ erg s}^{-1}.
\]  

Figure 1 shows the allowed region of the synchrotron luminosity as a function of $Y$ [59]. Two nearby sources, Cen A and M87, have good enough spectral coverage for a reliable measurement of the synchrotron peak and the $Y$ parameter. Both fall within the excluded region for acceleration of UHECRs to $10^{20}$ eV, unless UHECRs are composed of heavy nuclei. We point that for $Y \gg 1$, the electrons can rapidly cool, leading to a broad band emission spectrum [28]. In this scenario, it would not be possible to identify both the synchrotron and the IC peaks, and the analysis could not be carried out.

\textbf{Emission from AGN lobes.} While acceleration of UHECRs in the inner regions of AGNs are excluded by the data on Cen A and M87, jets from radio loud AGNs extend out to hundreds of kpc. Thus, additional possible acceleration sites exist in the turbulent outflow or at the termination shock of the giant AGN lobes.

Due to the large distance from the source, the seed photons for the IC scattering in this region are not the synchrotron photons, but rather photons originating from the cosmic microwave background (CMB) or extra-galactic background light (EBL). The incoming flux of the seed photons is therefore $\nu_{\text{F}_\nu})_{\text{peak,inc}} = \pi r^2 \nu_{\text{ex}} / 4\pi d_L^2$, where $r = R_{\text{acc}}$ is the characteristic size of the acceleration region, and $\nu_{\text{ex}}$ is the energy density of the CMB/EBL radiation fields. Substituting this result in the definition of $\bar{R}$ in equation (5), one obtains the minimum radius which allows acceleration of UHECRs,

\[
R_{\text{acc}} \geq \left(\frac{(\nu_{\text{F}_\nu})_{\text{peak,IC}}}{(\nu_{\text{F}_\nu})_{\text{peak,syn}}}\right)^{1/2} \left(\frac{\nu_{\text{ex}}}{4}\right)^{1/2} \left(\frac{\eta E_{\text{kin}}}{Z q}\right)^{1/2} \beta D
\]

\[
= 35 \left(\frac{(\nu_{\text{F}_\nu})_{\text{peak,IC}}}{(\nu_{\text{F}_\nu})_{\text{peak,syn}}}\right)^{1/2} \left(\frac{\nu_{\text{ex}}}{2}\right)^{1/2} \beta D \text{ kpc}.
\]
in evaluating the minimum radius in the second line of equation (4), we conservatively used $u_{\text{CMB}} \approx 4 \times 10^{-13}$ erg cm$^{-3}$. While several models exist for the energy density of the EBL light [29], it is generally smaller, $u_{\text{EBL}} \sim 10^{-14}$ erg cm$^{-3}$. Thus, if EBL photons are the target photons, a tighter constraint on the acceleration radius is obtained. The allowed region is plotted in Figure 2 [60].

Acceleration of UHECRs in Cen A. At distance of $\approx 3.7$ Mpc [31], Cen A is the nearest AGN. Due to its proximity, it was long been considered as a possible source of UHECRs [32, 33]. A renewed interest in its ability to produce UHECRs was prompted recently by the realization that the arrival directions of two and potentially even four UHECRs coincide within errors with its position [34, 35]. By analyzing VLA data, [37] concluded that the inner jet is trans-relativistic, $\beta \sim 0.5$, with Doppler shift $D \gtrsim 1$. A similar conclusion was recently drawn by the Fermi team [25], where $D \sim$ few was estimated, based on broad-band fits to the spectrum.

Emission from Cen A’s giant radio lobes, which extend to $\gtrsim 300$ kpc, was recently resolved by the Wilkinson Microwave Anisotropy Probe (WMAP) [38]. By analyzing the data and estimating the magnetic field strength and the jet magnetic luminosity, it was suggested by Ref. [38] that the giant lobes are possible acceleration sites of UHECRs. The giant lobes were later resolved by the Fermi observatory [30], constraining $(\nu F_\nu)_{\text{peak,IC}}/(\nu F_\nu)_{\text{peak,syn}} \gtrsim 10$.

The results presented in Figures 1 and 2 which are based on broad band data, show that the core region of Cen A does not fulfill the requirements that would enable it to accelerate protons to 10$^{20}$ eV. However, the results presented in equation (1) and Figure 2 do not rule out the proposal [38] that acceleration to 10$^{20}$ eV could occur in the outer regions of the giant lobes. Using the additional data enabled by Fermi, we add a constraint on the minimum acceleration radius to be $\gtrsim 110$ kpc.

An upper limit on the flux of UHECRs from Cen A is obtained by assuming that all 13 events seen within 18$^\circ$ of Cen A [39] indeed originate from its lobes. This implies an observed cosmic rays flux $J \approx 2 \times 10^{-17}$ m$^{-2}$s$^{-1}$sr$^{-1}$, which is translated into luminosity $\sim 4\pi d^2 \int J F_\nu \approx 10^{38} \text{erg s}^{-1}$. This value is about three orders of magnitude less than the synchrotron luminosity of Cen A (see Figure 1), implying energetic consistency, even when interpolating the UHECRs flux to lower energies, provided that the power law index is not significantly greater than 2.

Discussion. We derived constraints on the ability of AGNs to accelerate UHECRs. These constraints are set as limits on observable quantities, in particular the synchrotron peak luminosity and the ratio of IC to synchrotron peaks. We showed in equation (1) and Figure 1 that the inner core regions of Cen A and M87 do not fulfill the necessary requirement, and therefore cannot be sources of UHECRs at 10$^{20}$ eV, unless UHECRs are composed of heavy nuclei.

On the other hand, we showed that outer regions of gi-
ant radio lobes, which are frequently seen in radio galaxies, are possible acceleration sites. Using WMAP and Fermi data, we derived in equation (7) and Figure 2 the constraint that the acceleration site of the closest radio galaxy, Cen A, must be $\gtrsim 110$ kpc.

A common criticism of the possibility that AGNs might be the main sources of UHECRs is the lack of sources with bolometric luminosity $L_{\text{bol}} > 10^{46}$ erg s$^{-1}$ within the GZK horizon [e.g., 10, 11, and references therein], requiring potentially bright flares [12] [but see 13]. However, the origin of this requirement lies in the assumption of equipartition of energy between photons and magnetic field, and is therefore not of general validity.

Indeed, due to the difficulty in measuring the magnetic field strength, equipartition (or close to it) is often assumed [13, 16, 44, 45]. Based on this assumption it was claimed by [16] that AGN cores are plausible acceleration sites. However, this claim did not consider the limitation of the observed luminosity in nearby AGNs. Moreover, as was shown in [13], energetic protons cannot escape inner regions without significantly energy loss due to photopion production, which limits the maximum energy of observed UHECRs. It was further pointed out by Ref. 16 that acceleration of CRs to high energies during flaring activities is limited due to insufficient residence time in the accelerated region.

We presented a refined analysis, based on identification of the synchrotron and the IC peaks in broad band spectra of AGNs, which became available for Cen A and M87 through observations by the Swift and Fermi observatories. By doing so, we removed any dependence on the limited validity of the equipartition assumption. This analysis applies to ‘dark’ sources, namely those sources in which the energy density in the magnetic field is much larger than the energy density in the photon field. This is indeed the case for the giant radio lobes of Cen A, where at $\sim 100$ kpc, the data shows that the ratio of magnetic to photon energy densities is $\sim 10^6$ [38].

A detailed spectral analysis of many blazars was carried by [17]. In this analysis, a leptonic model (synchrotron and synchrotron self-Compton) was used to fit the broad band spectra of 73 nearby blazars (all of which are outside the GZK horizon). The obtained fits thus do not rely on the equipartition assumption. This analysis is therefore very similar to the one presented here, even more detailed. The fact that many blazars were found to have similar spectral shapes thus hints towards a possible generalization of our key results to many nearby AGNs.

Using values obtained in a similar fitting to the broad band spectra in Cen A [48], it was claimed by [49] that the core region of Cen A is excluded as an acceleration site of UHECRs. This conclusion is similar to the conclusion derived here, based on a much newer and better quality Fermi data. The analysis carried by Ref. 49, however, did not consider the external giant radio lobes.

In the analysis presented here we use a simplified assumption, namely that the electrons are mono-energetic. Thus, we ignore the energy distribution, which is needed for full spectral fits. Nonetheless, including a broad band spectral fitting, as was done, e.g., in Ref. 25 does not change any of our conclusions. This is because only a small fraction of the electrons are being accelerated to high energies, and most of the emission occurs near the electron energy responsible for the synchrotron peak. This was verified by comparing numerical modeling of GRB spectra to simplified analytical approximations [50].

While our analysis excluded the core regions of Cen A and M87 (and plausibly other nearby AGNs) from being sources of UHECRs, giant flares may change this conclusion. However, no measurement of the Compton parameter during flares exists. If such a measurement becomes available, it could further constrain the ability of AGN cores to produce UHECRs during flaring activities.

While existing data excludes the cores of Cen A and M87 from being potential acceleration sites of protons to $10^{20}$ eV, this is not the case if UHECRs are composed of heavy nuclei. Recent data collected by the Pierre Auger Observatory (PAO) show clues for heavy composition [51]. This data, however, is in contrast to the results obtained by the HiRes detector [52], and is therefore tentative. We point out though, that if indeed UHECRs are composed of heavy nuclei, not only the cores of radio loud AGNs are potential acceleration sites, but so many other objects, such as radio quiet AGNs [23].

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