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# Cen A as $\gamma$- and UHE cosmic-ray Source

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**Abstract.** Cen A has been recently detected in the high-energy (HE) and very high energy (VHE) $\gamma$-ray domain by Fermi-LAT and H.E.S.S. We review the observed characteristics and suggest a scenario where the VHE emission originates from the vicinity of the black hole. Motivated by the possible association of some ultra-high energy (UHE) cosmic ray (CR) events with Cen A, we further analyze the acceleration efficiency for a number of a mechanisms (including shock and stochastic acceleration), showing that most of them (apart perhaps from shear) have serious difficulties in accelerating protons beyond a few $10^{19}$ eV.

**Key words.** Gamma-rays: active galaxies – Radiation mechanism: non-thermal - Cosmic rays: origin

## 1. Introduction

Cen A is the nearest active galaxy, less than 4 Mpc away. It has a peculiar radio morphology with two jets emerging from its nucleus, and giant radio lobes stretching out to 250 kpc and extending over a 8 x 4 degree field on the sky (for review, see e.g. Israel 1998). VLBI studies have shown that Cen A is a non-blazar source with its jet inclined at viewing angles $i \gtrsim 50^\circ$ and characterized by moderate bulk flow speeds of $u_j \simeq (0.1-0.5)$ c only (Tingay et al. 1998; Hardcastle et al. 2003; Müller et al. 2011). Cen A harbors a supermassive black hole (BH) of mass $m_{\rm BH} = (0.5-3)\times 10^8 M_\odot$ (Marconi et al. 2006; Neumayer et al. 2007). Given its estimated bolometric luminosity $\sim 10^{43}$ erg/s (Whysong & Antonucci 2004), Cen A is rather under-luminous and believed to accrete at sub-Eddington rates. If its inner disk would remain cooling-dominated (standard disk), accretion rates $\dot{m} \sim 10^{-3}\dot{m}_{\rm Edd}$ and equipartition magnetic field strengths close to the BH of $B_0 = (2L_b/r_g^2 c)^{1/2} \simeq 2\times 10^3$ G are expected ($r_g = GM/c^2$ is the gravitational radius). If the disk would switch to a radiatively inefficient (RIAF) mode, characteristic field strengths may reach $B_0 \sim 10^4$ G.

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## 2. Gamma-rays from Cen A

Cen A was the only non-blazar AGN detected at MeV to GeV energies by all instruments on board the Compton Gamma-Ray Observatory (for review, see Steinle 2010). Fermi-LAT has recently reported HE (> 0.2 GeV) $\gamma$-rays from both the giant radio lobes and the "core" (i.e., within $\sim 0.1^\circ$) of Cen A (Abdo et al. 2010a,b): Both lobes have been detected up to 3 GeV, with step spectral slopes (photon indices close to 2.6), and contribute more than one-half to the total HE source emission. The HE lobe emission can be modeled as due to Compton up-scattering of CMB ($\epsilon = 8\times 10^{-4}$ eV) and infrared extragalactic background photons by electrons with Lorentz factors $\gamma_e = 6 \times 10^5$, assuming fields strengths $B \simeq 0.9\mu$G. This would imply a total energy (assuming a negligible proton contribution) in both lobes of $E_t \simeq 10^{58}$ erg, and require a jet kinetic power $L_j \simeq 8 \times 10^{42}$ erg/s close to the available accretion power. Fermi-LAT has also reported HE emission up to 10 GeV from the core, again with a steep photon index of $\sim 2.7$ and with apparent (isotropic) luminosity $L(> 0.1\,\mathrm{GeV}) \simeq 4 \times 10^{40}$ erg/s. The HE light curve (using 15 d bins) is consistent with no variability.

VHE ($> 0.1$ TeV) emission up to 5 TeV has been detected by H.E.S.S. in more than 100h of data taken in between 2004-2008 (Aharonian et al. 2009). The VHE spectrum is consistent with a power-law of photon index $2.7 \pm 0.5$, and the apparent (isotropic) luminosity is $L(> 250\,\mathrm{GeV}) \simeq 2 \times 10^{39}$ erg/s. No significant variability has been found.

The nuclear SED of Cen A, based on non-simultaneous data, shows two peaks, one at several $10^{13}$ Hz and one at around 0.1 MeV (Chiaberge et al. 2001; Meisenheimer et al. 2007; Abdo et al. 2010b). The SED below a few GeV is satisfactorily described by a one-zone synchrotron self-Compton (SSC) model (e.g., Chiaberge et al. 2001). As it turns out, however, the same approach fails to account for the TeV emission observed by H.E.S.S (Abdo et al. 2010b). In fact, a simple extrapolation of the Fermi (power law) spectrum tends to under-predict the observed TeV flux. This could indicate an additional contribution to the VHE domain beyond the conventional SSC jet emission, emerging at the highest energies. Non-thermal processes in the black-hole magnetosphere could offer a plausible explanation for this (Rieger & Aharonian 2009): Provided the inner disk in Cen A is radiatively inefficient (ADAF-type), electrons can be centrifugally accelerated along rotation magnetic field lines to $\gamma_e \propto 1/(1 - r/r_\mathrm{L}) \sim 5 \times 10^7$ while approaching the light cylinder $r_\mathrm{L} = c/\Omega$, and thereby enable Compton up-scattering of sub-mm ADAF disk photons to the TeV domain, satisfying the observed VHE spectral and luminosity constraints. If the inner disk is of the ADAF-type, these VHE photons can also escape $\gamma\gamma$-absorption. Observationally, the nuclear SED of Cen A peaks in the mid-infrared, with an apparent (isotropic) spectral luminosity of $\sim 6 \times 10^{41}$ erg/s at $h\nu \sim 0.15$ eV and evidence for an exponential cut-off (!) towards higher frequencies (Whysong & Antonucci 2004; Meisenheimer et al. 2007). This emission is usually believed to be produced on larger scales, either by a non-thermal (non-isotropic!) synchrotron jet component at a distance $\gtrsim 0.03$ pc (e.g., Meisenheimer et al. 2007) or a (quasi-isotropic) dusty torus on scales $\sim 0.1$ pc or larger (e.g., Radomski et al. 2008), thereby enabling sufficient dilution such that VHE photons are able to escape.

## 3. UHE cosmic rays from Cen A

The apparent clustering of UHECRs along Cen A has renewed the interest into nearby AGN as potential UHECR accelerators. In 2007, the Pierre Auger (PAO) Collaboration initially reported evidence for an anisotropy at the 99% confidence level in the arrival directions of cosmic-rays with energies $\gtrsim 6 \times 10^{19}$ eV (Abraham et al. 2007). The anisotropy was measured by the fraction of arrival directions that were less than $\sim 3°$ from the positions of nearby AGN (within 75 Mpc) from the VCV catalog. While this correlation has become weaker given the now available (twice as large) data set, the updated analysis still suggests that a region of the sky around the position of Cen A has the largest excess of arrival directions relative to isotropic expectations (Abreu et al. 2010). This obviously motivates a theoretical investigation of possible UHECR acceleration sites in Cen A. Below we analyze the efficiency constraints expected for a number of acceleration mechanisms when applied to Cen A. As it turns out, most mechanisms have serious difficulties in accelerating protons beyond a few $10^{19}$ eV. While the experimental situation is not fully conclusive yet, this result may fit into recent PAO indications for an increase of the average mass composition with rising energies up to $E \simeq 10^{19.6}$ eV (Abraham et al. 2010).

### 3.1. CR acceleration in the BH vicinity

Rotating magnetic fields, either driven by the disk or the BH itself, could facilitate acceleration of charged particles:

**(i) Direct electric field acceleration:** If the BH is embedded in a poloidal field of strength $B_p$ and rotating with angular frequency $\Omega_H$, it induces an electric field of magnitude $|\boldsymbol{E}| \sim (\Omega_H r_H) B_p/c$. This corresponds to a voltage drop across the horizon $r_H$ of magnitude $\Phi \sim r_H|\boldsymbol{E}|$. For Cen A, this voltage drop becomes

$$\Phi \sim 3\times 10^{19} a \left(\frac{m_{\rm BH}}{10^8 M_\odot}\right)\left(\frac{B_p}{10^4 \mathrm{G}}\right)\ [\mathrm{V}]\,, \qquad (1)$$

where $0 \le a \le 1$ denotes the dimensionless spin parameter. If a charged particle (charge number $Z$) could fully tap this potential, acceleration to $E = Ze\Phi \sim 3\times 10^{19} Z$ eV may become possible. This would favor a rather heavy composition (e.g., irons instead of protons) above $E_c = 5\times 10^{19}$ eV. Yet, whether such energies can indeed be achieved seems questionable: First, the charge density produced by annihilation of MeV photons emitted by an ADAF in Cen A most likely exceeds the Goldreich-Julian (GJ) density required to screen the electric field (Levinson & Rieger 2011). A non-negligible part of the electric field would then be no longer available for particle acceleration. Secondly, even if screening could be avoided, curvature losses (Levinson 2000) would constrain achievable energies for protons to

$$E_p \lesssim 10^{19} a^{1/4}\left(\frac{M}{10^8 M_\odot}\right)^{1/2}\left(\frac{B_p}{10^4 \mathrm{G}}\right)^{3/4}\ \mathrm{eV}. \qquad (2)$$

Thirdly, large-scale poloidal fields with strengths $B_p \sim 10^4$ G would be required. This seems overly optimistic, at least for a standard disk (Livio et al. 1999). Fourthly, one would need $a \simeq 1$ although rather moderate spins are expected for FR I sources (Daly 2011). Therefore, efficient DC acceleration of protons to $E_c$ and beyond in Cen A is unlikely, but could be possible for heavier elements.

**(ii) Centrifugal particle acceleration:** Even if the charge density would exceed the GJ density, centrifugal particle acceleration along rotating magnetic field lines could still occur (e.g., Osmanov et al. 2007; Rieger & Aharonian 2009). Yet, requiring that the acceleration timescale remains larger than the inverse of the relativistic gyro-frequency, CR Lorentz factors are limited to

$$\gamma \lesssim 2\times 10^7 \gamma_0^{1/3} Z^{2/3}\left(\frac{m_p}{m_0}\right)^{2/3}\left(\frac{r_{\rm L}}{10^{14}\mathrm{cm}}\right)^{2/3} \qquad (3)$$

where $r_{\rm L}$ is the light cylinder radius (typically of a few $r_g$). This suggests that centrifugal acceleration is unable to produce UHECRs.

### 3.2. Fermi-type CR acceleration in the jets and beyond

Suppose instead that CR acceleration is Fermi-type, i.e., due to multiple scattering off moving magnetic inhomogeneities, with a small energy change in each scattering event. We may then distinguish the following scenarios:

**(i) Diffusive shock (1st order Fermi):** In this case, energetic charged particles are assumed to pass unaffected through a shock front and, by being elastically scattered in the fluid on either side, to cross and re-cross it several times. Sampling the difference $\Delta u$ in flow velocities across a shock (always head-on), the characteristic energy gain for a particle crossing the shock, becomes 1st order, i.e., $\Delta\epsilon/\epsilon_1 \propto (\Delta u/c)$. As this is acquired during a shock crossing time $t_c \sim \lambda/u_s$ (with $u_s$ the shock speed and $\lambda$ the scattering mean free path), the characteristic acceleration timescale (for a non-relativistic shock) becomes

$$t_{\rm acc} \simeq \frac{\epsilon}{(d\epsilon/dt)} \simeq \left(\frac{\epsilon_1}{\Delta\epsilon}\right) t_c \simeq \lambda\frac{c}{u_s^2}\,. \qquad (4)$$

We can equate $t_{\rm acc}$ with the timescale for cross-field diffusion out of the system, $t_e \sim r_w^2/(\lambda c)$, or the dynamical timescale, $t_d \sim z/u_s$ (whichever is smaller), to obtain an estimate for the maximum achievable particle energy, $E_{\rm max} \simeq ZeBr_w\beta_s$ (cf. Hillas 1984), i.e.

$$E_{\rm max} \simeq 2\times 10^{19} Z\left(\frac{B_0}{10^4\mathrm{G}}\right)\left(\frac{\beta_s}{0.1}\right)\ \mathrm{eV}\,, \qquad (5)$$

assuming $\lambda \sim r_{\rm gyro}$, with $r_{\rm gyro}$ the gyro-radius, $\beta_s = u_s/c$, and $B(z) \simeq 4\ B_0\ (r_g/z\alpha_j)$ for the typical magnetic field strength at location $z$ (allowing for magnetic field compression by a factor of 4). Here, $\alpha_j$ is the jet opening angle. Radio observations of Cen A indicate bulk flow speeds, both (!) on sub-pc and hundreds of pc scales, that are only mildly relativistic. This suggests only moderate internal shock speeds, $\beta_s \lesssim 0.2$. Modest shock speeds are also supported by the nuclear SED of Cen A with a synchrotron peak below $10^{20}$ Hz (cf. Lenain et al. 2008) as synchrotron-limited electron shock acceleration results in a (magnetic field-independent) peak at $\sim 3 \times 10^{19} (\beta_s/0.1)^2$ Hz. Thus, efficient shock acceleration of protons to energies $E_c$ and beyond seems unlikely. Moreover, it can be shown that otherwise also a jet power well in excess of the one expected for Cen A as an FR I-type source would be required (Rieger 2009).

**(ii) Stochastic 2nd order Fermi:** In general, the average energy gain due to scattering off randomly moving magnetic inhomogeneities (waves) is only second order, i.e., $\Delta\epsilon/\epsilon_1 \propto (u/c)^2$. As the energy gain is acquired over a mean scattering time $t_s \sim \lambda/c$, the characteristic acceleration timescale is

$$t_{\rm acc} \sim \frac{\epsilon}{(d\epsilon/dt)} \sim \left(\frac{c}{v_A}\right)^2 \frac{\lambda}{c}\,, \tag{6}$$

assuming that scattering is due to Alfvén waves moving with $u = v_A = B/\sqrt{4\pi\rho}$. Neglecting radiative losses, particle energies are limited by escape via cross-field diffusion to

$$E \lesssim 2 \times 10^{19} Z \left(\frac{R}{100\ \rm kpc}\right)\left(\frac{v_A}{0.1\ c}\right)\left(\frac{B}{1\mu\rm G}\right) \rm eV$$

on scales of $R \sim 100$ kpc, appropriate for the giant radio lobes in Cen A. Stochastic UHE proton acceleration in its lobes (as suggested in Hardcastle et al. 2009) would thus require Alfvén speeds $v_A \geq 0.3$ c. This seems difficult to achieve (cf. also O'Sullvian et al. 2009). Thermal X-ray emission from the lobes Isobe et al. 2001 suggest (thermal) plasma densities of $n_{\rm th} \simeq (10^{-5} - 10^{-4})$ cm$^{-3}$, implying $v_A \lesssim 0.003$ c. Such values for $n_{\rm th}$ are consistent with independent estimates based on Faraday rotation measurements (Feain et al. 2009). Efficient UHECR acceleration in the lobes seems thus rather unlikely.

**(iii) Shear acceleration:** If the flow profile is non-uniform across the jet, as in the case of a shear flow with $\boldsymbol{u} = u_z(r)\boldsymbol{e}_z$, then energetic particles scattered across it, may be able to sample the flow difference $du$ and thereby get accelerated (Jokipii & Morfill 1990; Rieger & Duffy 2006). Like stochastic 2nd order Fermi, the average energy gain is $\propto (du/c)^2$, although the physical origin is different (i.e., due to the systematic, instead of the random motion of the scatterers). The velocity difference, that a particles experiences, is $du \sim (du_z/dr)\lambda$, where $\lambda$ is the scattering mean free path. Again, this energy change is acquired over $\tau_s \sim \lambda/c$, so that

$$t_{\rm acc} \sim \frac{\epsilon_1}{\Delta\epsilon/\tau_s} \sim \frac{1}{(du_z(r)/dr)^2}\frac{c}{\lambda}\,. \tag{7}$$

In contrast to eq. (4) and eq. (6), now $t_{\rm acc} \propto 1/\lambda$. Thus, $t_{\rm acc}$ becomes smaller as a particle increases its energy (so that its $\lambda \propto p^\alpha$, $\alpha > 0$, becomes larger). Shear acceleration therefore preferentially picks up high-energy seed particles for further energization, and acts more easily on particles of higher rigidity. Shocks, operating in the jet, could well provide the required seed particles (Rieger & Aharonian 2009). Achievable particle energies are then constrained by the confinement condition (i.e., $r_{\rm gyro} \leq$ width of the shear layer). The large-scale jet in Cen A has a projected length of about 4.5 kpc, and towards its end a width of about 1 kpc (Burns et al. 1983; Kraft et al. 2002). For a characteristic $B \sim 10^{-4} b_j$ G on kpc-scale (cf. magnetic flux conservation) and a width of the shear comparable to the width of the jet, maximum energies

$$E \sim ZeB(\Delta r) \sim 10^{20} b_j Z\ \rm eV \tag{8}$$

are possible. Shear acceleration might thus be able to boost energetic seed protons (e.g., produced by shock acceleration) to energies beyond $E_c$. If the magnetic field gets amplified by internal shear (e.g., Urpin 2006), even $b_j \gtrsim 1$ may be possible. Note that a shear dynamo could possibly explain why the magnetic field direction in Cen A seems to be almost parallel along its kpc jet (Hardcastle et al. 2003).

## 4. Conclusions

The observed HE (Fermi) and VHE (H.E.S.S.) characteristics of Cen A (”core”) suggest that the HE and VHE emission originate from different regions. While the nuclear SED below a few GeV can be satisfactorily described with a conventional one-zone SSC model, an additional contribution is required to account for the VHE emission. Non-thermal processes in the black hole-jet magnetosphere could offer a plausible explanation for the latter.

Whether Cen A is indeed an UHECR source has observationally not been settled yet. From a theoretical point of view, efficient acceleration of protons to UHECR energies in Cen A remains challenging in the framework of most standard mechanisms. Observational evidence for UHE protons may therefore support the operation of an additional acceleration mechanism (”two-step”) such as shear. The situation is much more relaxed for heavier elements like iron nuclei, which could most likely be directly accelerated (either by shocks or within the BH magnetosphere) to UHECR energies. Note that simultaneous operation of several mechanisms (with maximum energy not always linearly dependent on charge) also seems to constrain the potential to infer the UHECR composition from the observed anisotropy (Lemoine & Waxman 2009).

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**DISCUSSION:**

**VALENTI BOSCH-RAMON:** Assuming ideal MHD in the jet launching region, how high can the particle Lorentz factor be?

**FRANK RIEGER:** In ideal (single-fluid) MHD models, the azimuthal component of the magnetic field increases on approaching the light cylinder, and this makes centrifugal (test) particle acceleration inefficient. The details are dependent on the assumed rotation law and current distribution along the field line. It is, however, not always clear whether ideal MHD can be applied close to the BH (cf. Levinson & Rieger 2011).