

# Centaurus A as a Cosmic Ray Accelerator

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**Abstract.** We consider the maximum energy of cosmic-ray nuclei in the radiation/magnetic environments found in active galactic nuclei (AGN) and apply our results to the case of Centaurus A. We also discuss the propagation of ultra-high energy (UHE) cosmic rays (CR) from Centaurus A and investigate whether the UHE CR observed by Auger from the general direction of Cen A could be due to acceleration in the jets and hot-spots as they are now, or if they could have been accelerated several Myr ago, when Cen A’s jets were more powerful, and are only now arriving.

## 1. Introduction

Arrival directions of the UHE CR detected by the Pierre Auger experiment above  $5.6 \times 10^{19}$  eV have been found to be statistically correlated with positions of nearby AGN (Abraham et al. 2007), and a few of the arrival directions appear to be clustered around Centaurus A, our nearest active galactic nucleus at a distance of  $\sim 3.8$  Mpc. This has led to speculation that Centaurus A may be responsible for some of the UHE CR. We consider the acceleration of such cosmic-ray protons and nuclei in astrophysical environments which may be found in and around AGN, taking into account all the relevant interaction processes with photon backgrounds.

Protons and nuclei being accelerated in or propagating through the intergalactic medium interact mainly with the cosmic microwave background (CMB), and infrared, optical and ultraviolet (IR/Opt/UV) photon backgrounds. These interactions produce features in the propagated UHE CR spectrum such as the “GZK cutoff” (Greisen, 1966; Zatsepin & Kuzmin, 1966). Nuclei suffer Bethe-heitler pair production, but more importantly suffer photo-disintegration (Puget et al., 1976).

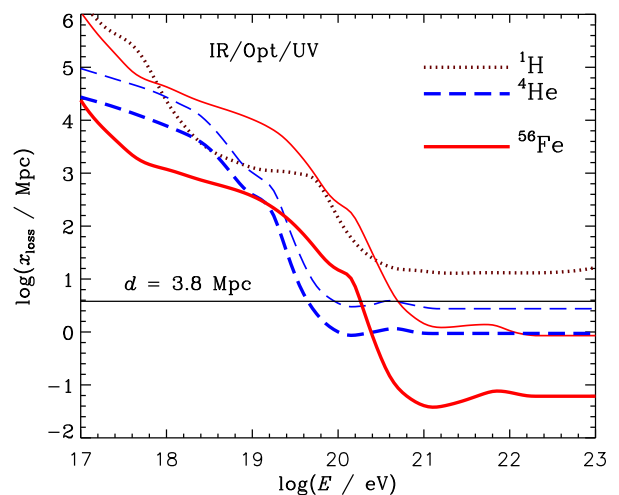
With Centaurus A only 3.8 Mpc away, and with the pion photo-production energy-loss distance on the CMB minimizing at  $\sim 12$  Mpc above  $10^{11}$  GeV (e.g. Protheroe 2004) for rectilinear propagation one would observe UHE CR protons almost unattenuated by pion photo-production interactions on the CMB. Rieger & Aharonian (2009) suggest that shear acceleration along the kpc jet may accelerate protons beyond  $5 \times 10^{19}$  eV. See also Kachelriess et al. (2009a, 2009b). The magnetic field of Centaurus A’s giant lobes (Feain et al. 2009) may also provide an environment suitable for acceleration of UHE CR (Benford & Protheroe 2008; Hardcastle et al. 2009).

GeV energy gamma-rays have been observed from Cen A at GeV energies by Fermi-LAT (2010) and by HESS at TeV energies (Aharonian et al. 2009). A summary of neutrino flux limits for Cen A over the energy range above

$10^{17}$  eV is given by James et al. (2010), although they are not yet sensitive enough to seriously constrain models.

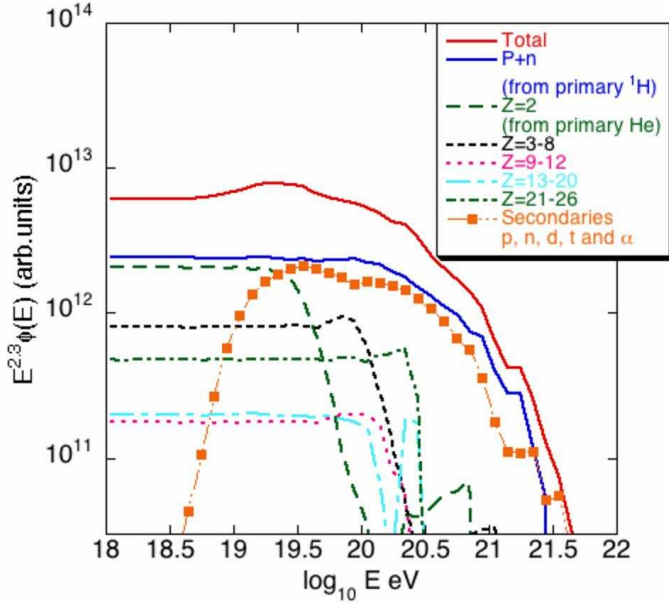
## 2. Attenuation of protons and nuclei in background radiation

To model interactions with radiation we use the SOPHIA event generator for pion photo-production (Mücke et al., 2000), continuous energy loss for Bethe-Heitler (BH) pair production (Rachen 1996) and the photon-nucleus interaction event generator developed by Allard et al. (2005, 2006, 2007, 2008) – see these papers for references to the original data compilations and fits. For the photon backgrounds in the infra-red, optical and ultra-violet window, we use an estimate by Stecker et al. (2005).



**Fig. 1.** Loss distances (upper curves) and mean free paths (lower curves) for helium and iron nuclei in the CMB plus IR/Opt/UV radiation fields (from Allard & Protheroe 2009) plotted against energy. Loss distance of protons is also shown. The distance to Cen A is indicated.

In Fig. 1 we show the dependence of the loss (or attenuation) length for cosmic-ray protons, helium and iron

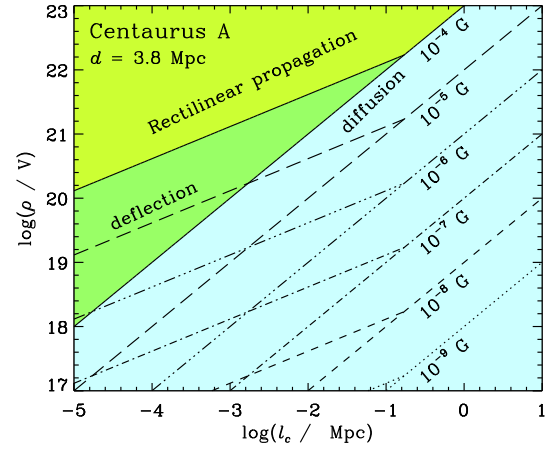


**Fig. 2.** Propagation of a galactic mixed composition with an  $E^{-2.3}$  spectrum and  $E_{\max} = Z \times 10^{21}$  eV over 3.8 Mpc (D. Allard, private communication)

nuclei, and the mean free paths of helium nuclei and iron nuclei in the CMB plus intergalactic IR/Opt/UV background as a function of energy. The loss length for CR protons is  $x_{\text{loss}}(E) = cE/[dE/dt]$  where  $dE/dt$  is an effective energy loss rate for Bethe-Heitler pair production and pion photo-production on the ambient radiation field. The loss length for nuclei of atomic mass  $A > 1$  is  $x_{\text{loss}}(E) = cA/[dA/dt]$  where  $dA/dt$  is the average rate of loss of nucleons from the nucleus by photo-disintegration, and is somewhat longer than the mean free path by a factor slightly less than  $A$ . In determining the survival probability of compound nuclei the mean free path is relevant, and we see immediately that for rectilinear propagation over 3.8. Mpc, no iron nuclei will survive above an energy of  $1.8 \times 10^{20}$  eV, and no helium nuclei will survive above an energy of  $4 \times 10^{19}$  eV. However where the path-length is only a few mean free paths heavy nuclei resulting from photo-disintegration of iron would be present.

As an example of a full calculation propagation of nuclei over 3.8 Mpc we show in Fig. 2 we show the result of the propagation for  $B = 0$  of a galactic mixed composition with an  $E^{-2.3}$  spectrum and  $E_{\max} = Z \times 10^{21}$  eV. One can see that the cut off for the heaviest component (arbitrarily as  $Z > 20$ ) occurs before the crossing on the loss length plot. This is because the notion of “survival” of a nucleus is somewhat arbitrary.

The presence of an intergalactic magnetic field increases the travel-times of CR from Cen A, either as a result of magnetic deflection at high energies, or at lower energies by diffusive propagation. Propagation in a magnetic field with a domain-like structure will have a different rigidity dependence to that of diffusion. Sigl et al. (2003) estimate the travel time for UHE CR from distance



**Fig. 3.** The  $\rho-l_c$  space is divided into regions in which the propagation can be described as diffusion, rectilinear or deflection for  $B = 10^{-4}$  G (solid lines),  $B = 10^{-5}$  G (long dashed lines), ...  $B = 10^{-9}$  G (dotted lines).

$d$  through the intergalactic field to be

$$ct_{\text{def}}(\rho, d) = 0.045 \left( \frac{\rho}{10^{20} \text{ V}} \right)^{-2} \times \left( \frac{d}{1 \text{ Mpc}} \right)^2 \left( \frac{l_c}{\text{Mpc}} \right) \left( \frac{B}{10^{-7} \text{ G}} \right)^2 \text{ Mpc}$$

where  $l_c$  is the coherence length of the magnetic field, which is a few tens of kpc in clusters (Kotera et al. 2009). Ryu et al. (2008) estimate the magnetic field to be a few microgauss in clusters and groups. At rigidities above

$$\rho_{\text{rect}} = 2.1 \times 10^{19} \left( \frac{d}{1 \text{ Mpc}} \right)^{1/2} \left( \frac{l_c}{\text{Mpc}} \right)^{1/2} \left( \frac{B}{10^{-7} \text{ G}} \right) \text{ V}$$

cosmic ray propagate almost rectilinearly. At rigidities below

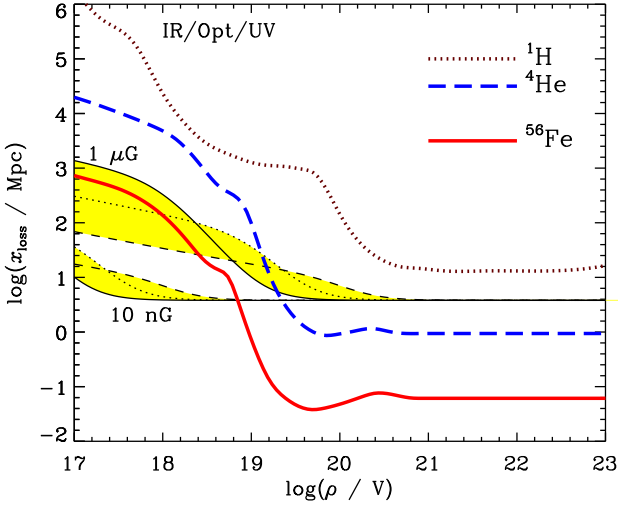
$$\rho_{r_g-l_c} = 10^{20} \left( \frac{l_c}{\text{Mpc}} \right)^{1/2} \left( \frac{B}{10^{-7} \text{ G}} \right) \text{ V}$$

the gyro-radius is less than the coherence length and cosmic rays propagate diffusively, and in this region

$$ct_{\text{diff}}(\rho, d) = ct_{\text{def}}(\rho_{r_g-l_c}, d) \left( \frac{\rho}{\rho_{r_g-l_c}} \right)^{-1/3}$$

Fig. 3 maps the  $\rho-l_c$  space for propagation from Cen A and shows which type of propagation will occur for the magnetic fields indicated.

In Fig. 4 we plot the loss distance of protons, and mean free paths of helium and iron nuclei in the CMB plus IR/Opt/UV radiation fields against rigidity  $\rho \approx E/Zc$  where  $E$  is the total energy and  $Z$  is the atomic number. The propagation time, multiplied by  $c$ , for  $B = 1 \mu\text{G}$  and  $B = 1 \text{ nG}$ , and  $l_c$  in the 10–100 kpc range. We see that the survival probability of iron nuclei, and even helium nuclei, is quite sensitive to the extragalactic magnetic field and its structure. For example, if  $B = 1 \mu\text{G}$  and  $l_c = 1$



**Fig. 4.** Loss distance of protons, and mean free paths of helium and iron nuclei in the CMB plus IR/Opt/UV radiation fields (from Allard & Protheroe 2009) plotted against rigidity. The propagation time, multiplied by  $c$ , is shown for  $B = 1 \mu\text{G}$  and  $B = 1 \text{nG}$  by the thin curves for  $l_c = 1 \text{kpc}$  (thin solid curves),  $l_c = 10 \text{kpc}$  (thin dotted curves), and  $l_c = 100 \text{kpc}$  (thin dashed curves).

kpc then no UHE CR Fe nuclei will survive at any energy. If  $B = 1 \mu\text{G}$  and  $l_c = 10 \text{kpc}$  all Fe nuclei above  $2.6 \times 10^{19} \text{eV}$  will be photo-disintegrated, and if  $B = 1 \mu\text{G}$  and  $l_c = 100 \text{kpc}$  all Fe nuclei above  $6.5 \times 10^{19} \text{eV}$  will be photo-disintegrated. Again, one should note that heavy nuclei from photo-disintegration of iron may be present at some level. In the case of He nuclei, if  $B = 1 \mu\text{G}$  and  $l_c = 10 \text{kpc}$  then above  $2.7 \times 10^{19} \text{eV}$  He nuclei will be photo-disintegrated, i.e. at an energy only marginally lower than for rectilinear propagation.

### 3. Acceleration

By plotting magnetic field vs. size of various astrophysical objects, Hillas (1984) identified possible sites of acceleration of UHE CR based on whether or not the putative source could contain the gyro-radius of the accelerated particles, and on the likely velocity of scattering centers in these sites, and narrowed the field of possible sources to radio galaxy lobes and galaxy clusters. In general, the maximum rigidity gain rate of relativistic particles can be written  $r_{\text{gain}}(\rho) \equiv (1/\rho)(d\rho/dt) = \xi(\rho)c^2B\rho^{-1}$  where  $\xi(\rho) < 1$  is the acceleration rate parameter which depends on the details of the acceleration mechanism, with  $\xi=1$  corresponding to the highest possible gain rate for any mechanism (see Protheroe 1998).

From the gain and the loss rates for proton or nucleus-photon interactions and synchrotron radiation, together with the maximum time available for acceleration, we can estimate the maximum energies of accelerated particles by solving

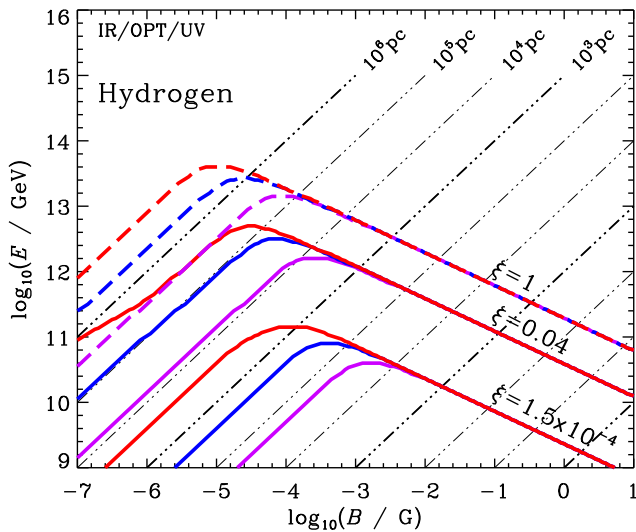
$$r_{\text{gain}}(E_{\text{max}}) - r_{\text{loss}}(E_{\text{max}}) - r_{\text{synch}}(E_{\text{max}}) - 1/t_{\text{max}} = 0.$$

This has been done for three values of  $\xi$  in Fig. 5 for proton for the standard IR/Opt/UV radiation field. For each  $\xi$ -value we show the result for  $ct_{\text{max}}=0.4 \text{Mpc}$ ,  $3.2 \text{Mpc}$ , and  $32 \text{Mpc}$ .

For an acceleration rate  $10^{-4}$  times the maximum possible, pion photo-production, finite size or maximum time available cuts off the spectrum for fields below  $\sim 100 \mu\text{G}$  and synchrotron losses cut off the spectrum for higher fields. In order to accelerate protons above  $10^{20} \text{eV}$  the ideal sources have acceleration region sizes (magnetic field) between  $1 \text{kpc}$  ( $\sim 1 \text{mG}$ ) and  $1 \text{Mpc}$  ( $\sim 1 \mu\text{G}$ ) such that the gyro-radius can be contained within the accelerator. These parameters allow the spectrum to extend beyond  $10^{20} \text{eV}$ . This makes radio galaxies and clusters of galaxies probable sites of UHE CR acceleration (see Fig. 6 of Protheroe 2004) in agreement with the conclusion of Hillas. Indeed, in a recent review, Biermann et al. (2008) concluded that the most promising contenders are radio galaxies and gamma-ray bursts (GRB). However, if the whole acceleration region is moving relativistically, Doppler boosting in energy of neutrons (produced by pion photo-production) escaping from such sources allows blazar jets (Protheroe et al. 2003) and GRB (Waxman 2006 and references therein) to remain possible sites of UHE CR acceleration, and in these cases proton synchrotron losses are likely to cut off the spectrum. Large-scale cosmic shocks in the Universe may also be sites of UHE CR acceleration (Kang & Jones 2002, Inoue et al. 2007) as well as colossal magneto-hydrodynamic fossil AGN structures (Benford & Protheroe 2008), AGN jets and cocoons surrounding AGN jets (Schopper et al. 2002, Norman et al. 1995) and hot spots in radio lobes of powerful radio galaxies (Rachen & Biermann 1993). In these cases pion photo-production, the finite size of the accelerator or the time available for acceleration may cause the cut-off in the spectrum of protons at acceleration.

### 4. Acceleration in the past when Cen A was more powerful

While now Cen A is now only a very weak AGN with a short jet just a few kpc long, it has a giant radio relic indicating that in the past it was probably a more powerful AGN, possibly a powerful radio galaxy as the radio relic extends several hundreds of kpc from the source with of comparable length in the past. Das et al. (2008) have simulated propagation of UHE CR through magnetized large scale structure and conclude that for observers located inside groups of galaxies like ours, about 70% and 35% of UHECR events above  $60 \text{EeV}$  arrive within  $15^\circ$  and  $5^\circ$ , respectively, of the source position with time delays of less than  $10^7 \text{yr}$ . So any CR we see now could have been accelerated 1 My earlier than the images in radio and optical we see now, i.e. when Cen A was probably a powerful radio galaxy (even though now Cen A is relatively weak). The magnetic field conditions at the far end of a historic more-powerful jet Cen A, may have been similar to FR II radio galaxies we see now with  $B = 0.3 \text{mG}$  and



**Fig. 5.** Maximum energy of protons in the CMB plus IR/Opt/UV radiation vs magnetic field for  $ct_{\max}=0.4$  Mpc (lower curves), 3.2 Mpc (middle curves), and 32 Mpc (upper curves) for each  $\xi$  value indicated.

$v_{\text{shock}} = 0.3c$ , and this would have given a high acceleration rate. Looking at Fig. 5 for acceleration in our standard IR/Opt/UV radiation we see that for  $B = 0.3$  mG and  $\xi = 0.04$  acceleration of protons to  $10^{21}$  eV in a  $\sim 3$  kpc size hot-spot at the end of a  $\sim 300$  kpc jet somewhere near the edge of the current giant lobes could have been possible. For the same parameters, iron nuclei would have been accelerated to about  $2.5 \times 10^{22}$  eV.

From Fig. 4 that delays of the order of a few Mpc are possible, and so, protons and Fe nuclei will have very different travel times. If Cen A was very active long ago but has not been as powerful over the past few Myr, then: (i) if  $B$  is small we should see no protons from Cen A, but we should see Fe nuclei from Cen A but not tightly correlated with Cen A direction; (b) if  $B$  is large we should see both protons and Fe, but not tightly correlated with Cen A direction.

## 5. Conclusion

UHE CR protons should reach us almost unattenuated from Cen A, while compound nuclei will suffer photo-disintegration on the CMB and IR/Opt/UV background radiation fields. No iron nuclei should survive above  $1.8 \times 10^{20}$  eV. However, as a result of magnetic deflection or diffusion, depending on the magnetic field and its coherence length travel times may be extended such that this maximum energy for survival of iron, and to a lesser extent other nuclei, may be significantly reduced. The presence or absence of iron nuclei in the energy range below  $1.8 \times 10^{20}$  eV may therefore provide some constraints on the magnetic structure of the intergalactic medium. Finally, the longer travel times (than the light-travel time) mean that in cosmic rays we see Cen A as it was at earlier

times than we see Cen A in the optical, when Cen A was possibly a more powerful AGN able to accelerate cosmic rays to well above  $10^{20}$  eV with sufficient cosmic ray luminosity to explain a substantial fraction of the observed UHE CR.

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