High energy radiation from Centaurus A

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***Abstract*. We calculated for the nearest active galactic nucleus (AGN), Centaurus A (Cen A), the flux of high energy cosmic rays and of accompanying secondary photons and neutrinos expected from hadronic interactions in the source. We used as two basic models for the generation of ultrahigh energy cosmic rays (UHECR) shock acceleration in the radio jet and acceleration in the regular electromagnetic field close to the core of the AGN, normalizing the UHECR flux to the observations of the Auger experiment. Here we compare the previously obtained photon fluxes with the recent data reported by the Fermi LAT and H.E.S.S. collaborations. In the case of the core model, we find good agreement both for the predicted spectral shape and the overall normalization between our earlier results and the H.E.S.S. observations for a primary proton energy $dN/dE \propto E^{-\alpha}$ with $\alpha \sim 2$ or smaller. A broken-power law with high-energy part $\alpha = -2.7$ leads to photon fluxes in excess of the Fermi measurements. The energy spectrum of the photon fluxes obtained by us for the jet scenario is in all cases at variance with the H.E.S.S. and Fermi observations.**

***Keywords*: Cosmic rays; γ rays; high energy neutrinos; active galactic nuclei, Cen A.**

I. INTRODUCTION

Progress in cosmic ray (CR) physics [1] has been hampered for long time by the deflection of charged cosmic rays in magnetic fields, preventing the identification of individual sources. This problem could be solved by using the neutral messengers that should be produced as secondaries in hadronic CR interactions close to the source. However, the secondary photons generated are difficult to disentangle from photons produced by synchrotron radiation or inverse Compton scattering of electrons. Moreover, high energy photons are strongly absorbed both in the source and propagating over extragalactic distances. By contrast, the extremely large mean free path of neutrinos together with the relatively poor angular resolution of neutrino telescopes and the small expected event numbers makes the identification of extragalactic sources challenging using only the neutrino signal. Performing neutrino astronomy beyond the establishment of a diffuse neutrino background requires therefore most likely additional input, either timing or angular information from high energy photon or CR experiments.

The recently announced evidence [2] for a correlation of the arrival directions of UHECRs observed by the Pierre Auger Observatory (PAO) with active galactic nuclei (AGN) may provide a first test case for successful "multi-messenger astronomy." In particular, Ref. [2] finds two events within the search bin of 3.1° around the nearest active galaxy, Centaurus A (Cen A). This FR I radio galaxy is located close to the supergalactic plane at a distance of about 4 Mpc (see Ref. [3] for more details). At present this correlation, not confirmed by the HiRes experiment [4], has only $3\,\sigma$ C.L. and other source types that follow the large-scale structure of matter would also result in an excess of events along the supergalactic plane. Note that the small distance to Cen A makes it conceivable that Cen A is the only source usable directly for UHECR astronomy (i.e. not only for e.g. auto-correlation studies [5]), while charged cosmic rays from other more distant souces are too strongly deflected.

In Ref. [6], we studied therefore the possibility to observe Cen A using high-energy photons and neutrinos. Taking the correlation signal at face value, we used the PAO results as normalization of the CR flux and calculated the flux of accompanying secondary photons and neutrinos expected from hadronic interactions in the source. Since both the Fermi LAT collaboration [7] and the H.E.S.S. collaboration [8] reported recently the discovery of γ-ray emission from Cen A, we have now the opportunity to check our predictions against these observations.

II. ASSUMPTIONS

We calculated the flux of high energy cosmic rays and of accompanying secondary photons and neutrinos expected from Cen A for two different scenarios: Acceleration close to the core, either in accretion shocks or regular electromagnetic fields, and acceleration in the radio jet. In the first case UV photons are the most important scattering targets. We modeled the primary photon field around the AGN core guided by the simplest possible theoretical model [9], namely the thermal emission from a geometrically thin, optically thick Keplerian accretion disc. The interaction depth for photo-hadron interactions can reach $\tau_{p\gamma} \sim$ few. According to the observational data we found that pp interactions of UHE protons with the gas provide the main source of CR interactions in the second scenario. In this case, moreover, diffusion in the turbulent magnetic fields will increase the interaction depth at low and intermediate energies. We considered also three spectra $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha}$ of the injected protons: Power-laws with $\alpha = 1.2$ and $\alpha = 2$, and a broken power-law with $\alpha = 2.7$ for $E > E_b = 10^{18}$ eV.

We based our calculations on several simplifying assumptions like the use of an one-dimensional geometry and the omission of the acceleration process. In particular, we only postulated that acceleration to 10^{20} eV is possible in the environment of Cen A, without demonstrating it for a concrete model. Finally, hadronic interactions are simulated with an extension of the Monte Carlo code described in Ref. [10].

III. Results versus observational data

Figure 1 displays the particle fluxes predicted [6] from Cen A as function of the energy, assuming that the two events observed by PAO around Cen A indeed originate from this AGN. The case of acceleration close to the core is shown on the left, while the case of acceleration in the jet is shown on the right. From the top to the bottom, spectra are displayed for a broken power-law, $\alpha = 2$, and $\alpha = 1.2$. In addition to the injected proton flux (black solid line), we show the flux of protons (black dashed), photons (blue solid) and neutrinos (red solid) arriving on Earth. Note that the cutoff in the neutrino and proton spectra below 100 GeV is artificial, since we neglect neutrinos and protons with lower energies in our simulation.

In the core model the final proton flux is reduced by photon-proton interactions by a factor ≈ 2 above the threshold energy $\sim 10^{16}$ eV (left), while diffusion in the jet increases the interaction depth for lower energies (right), resulting in the effective production of secondaries. Since the CR spectra are normalized to the integral UHECR flux above $E_{\rm th} = 5.6 \times 10^{19}$ eV, steeper spectra result in larger secondary fluxes at low energies. Note that the photon fluxes after cascading in the source are remarkeably insensitive to the shape of the proton flux. Hence the slope of the observed photon flux is a central predicition of Ref. [6].

While we could show earlier [6] these fluxes only together with an upper limit from H.E.S.S. and the estimated sensitivity of Fermi for point sources, we have updated now these figures with the recently published results from Fermi [7] and H.E.S.S. [8]. Remarkably, the photon flux in the Fermi and the H.E.S.S. energy range has approximately the same power-law exponent ($\alpha \sim 2.6$ and 2.7), but the latter requires a larger normalization constant. Such a behavior is expected, if a new component, e.g. of hadronic origin, sets in above 100 GeV, while at lower energies photons of electromagnetic origin dominate the spectrum. For a more detailed test of this hypothesis in the future, the differential energy spectrum at the high-energy end of the Fermi spectrum will be most useful.

The most important consequence of the recent H.E.S.S. results is to significantly disfavor the jet scenario. In spite of the uncertainties in the normalization, the almost flat spectrum predicted in this model is in contradiction with the shape of the γ-ray spectrum observed by H.E.S.S. Moreover, the angular extension of the photon flux observed by H.E.S.S. is consistent with a point source at the AGN core and excludes thereby the radio lobes as sources.

On the contrary, the shape of the γ-ray spectrum observed by H.E.S.S. agrees very well with the slope expected in the core model. The Fermi measurements restrict additionally the source model, excluding the broken-power law case that leads to an excessive photon fluxes in the GeV range. In summary, a primary proton energy $dN/dE \propto E^{-\alpha}$ with $\alpha \sim 2$ or smaller in the case of acceleration close to the core is consistent with the H.E.S.S. and Fermi observations, assuming that in the GeV range the photon flux has dominantly an electromagnetic origin.

Finally, we comment on the neutrino fluxes to be expected from Cen A. Calculating the expected event number in a neutrino telescope requires a definite choice of the experiment. Centaurus A is from the location of Icecube only visible from above, and thus the background of atmospheric muons allows only the use of contained events that carry essentially no directional information. By contrast, a neutrino telescope in the Mediterranean could make use of the muon signal and the directional information. The resulting event numbers both for cascade and shower event number per year observation time are summarized in Table I. For a discussion on the connection between Cen A as source of UHECRs and the associated diffuse neutrino flux see Ref. [11].

IV. Conclusions

In summary, the combination of data from PAO and H.E.S.S. is consistent with a scenario where the UHECRs observed by PAO are protons accelerated near the core. The VHE γ-rays detected by H.E.S.S. would then have a hadronic origin, namely, the interaction of the accelerated protons with the UV photons surrounding the core. This model is expected to be tested in the near future as the currently running PAO, H.E.S.S. and Fermi experiments increase their statistics.

Acknowledgments

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TABLE I
NUMBER OF NEUTRINO EVENTS EXPECTED PER YEAR.

	jet				core			
α or E_b/eV	1.2	2	10^{18}	10^{17}	1.2	2	10^{18}	10^{17}
contained # ν/yr	8×10^{-5}	0.02	0.4	2.0	7×10^{-4}	0.01	0.3	0.9
# μ/yr	4×10^{-5}	0.01	0.2	0.7	3×10^{-4}	7×10^{-3}	0.1	0.5

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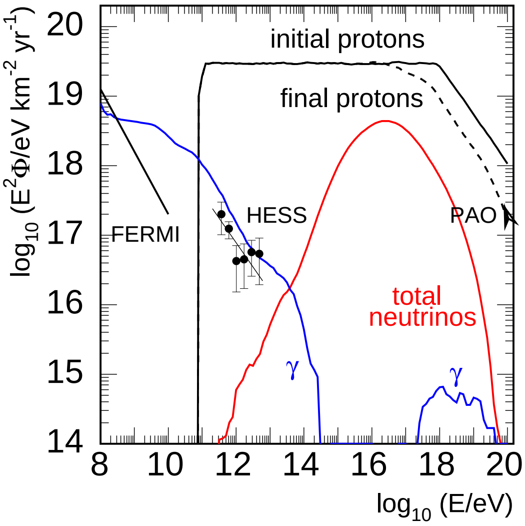
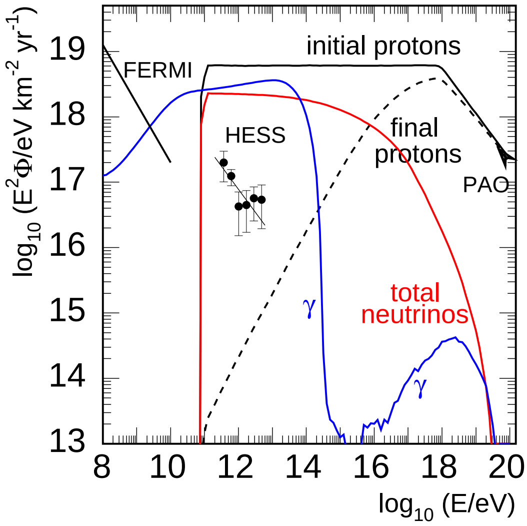


(a)



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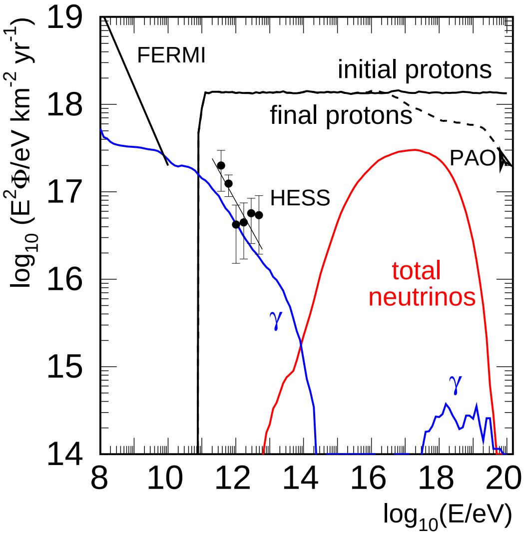

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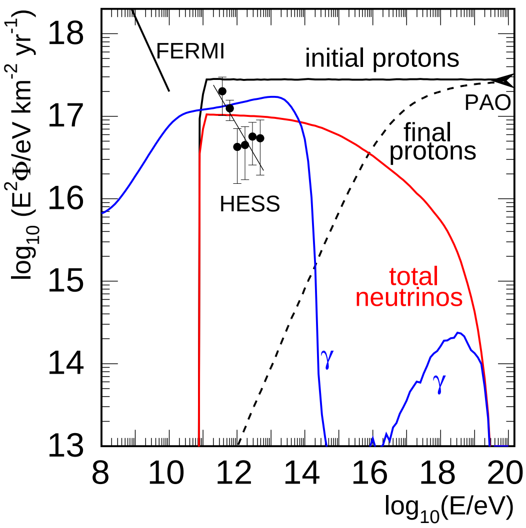

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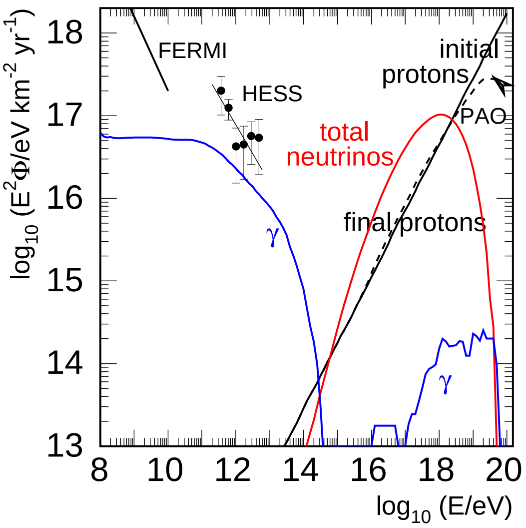

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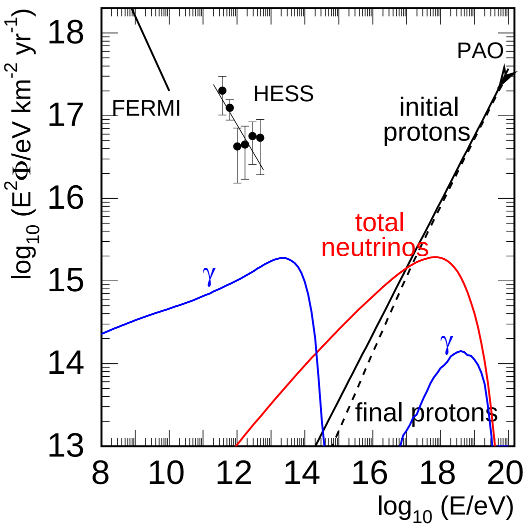

(f)

Fig. 1. Particle fluxes from Cen A normalized to the PAO results, see the text for a description. From Ref. [12].