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A MODEL FOR THE INNER JET HIGH-ENERGY EMISSION OF CENTAURUS A

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We investigate the spectral energy distribution (SED) of Centaurus A resulting from a steady compact acceleration region, located close to the central black hole, where both leptonic and hadronic relativistic populations arise. We present here results of such a model, where we have considered synchrotron radiation by primary electrons and protons, inverse Compton scattering, and gamma-ray emission originated by the inelastic hadronic interactions between relativistic protons and cold nuclei within the jets. Photo-meson production by relativistic hadrons were also taken into account, as well as the effects of secondary particles injected by all interactions. The internal and external absorption of gamma rays is shown to be of great relevance to shape the observable SED, which was also recently constrained by the results of Fermi and HESS.

Keywords: radiation mechanism: non-thermal – galaxies:active – galaxies: individual: Centaurus A.

1. Introduction

Centaurus A is the closest and best studied radio-loud AGN (a Fanaroff-Riley Class I galaxy). It is viewed from the side (∼ 70°) of the jet axis. The elliptical galaxy NCG 5128 is the stellar body of the giant double radio source. Cen A extends 10° on the sky, and it can be resolved down to sub-arcsecond scales in the inner radio structures which correspond to several pc because of its proximity (3.84 ± 0.35 Mpc, Ref. 1). The galaxy has an absorbing band of gas and dust projected on its stellar body. Linear radio/X-ray are ejected from the nucleus, becoming sub-relativistic at

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a few parsecs. At about 5 kpc from the core, the jets expand into plumes, and there are huge radio lobes that extend beyond the plumes out to 250 kpc. For extensive literature, visit the dedicated Cen A web page `http://www.mpe.mpg.de/Cen-A/`.

Cen A was detected[2] repeatedly by all the instruments (OSSE, COMPTEL, BATSE and EGRET) of the Compton Gamma-Ray Observatory (CGRO) and it has been included in the Fermi-LAT bright source list[3]. At very high energies (VHEs), previous tentative detections and upper limits were announced (e.g. Ref. 4) but only very recently a VHE spectrum has been measured by the HESS array[5]. All these observations, however, are not simultaneous[6], something which should be taken into account when pondering any model for the high-energy (HE) emission. Several authors have proposed that injection of relativistic protons can take place in active galaxies (see Ref. 7, and references therein). Because of this we propose a model for the emission from both hadronic and leptonic (primary and secondary) particles in a proton dominated jet, similar to what has been applied to galactic microquasars[8–10]. We aim at obtaining information on the physical parameters related to the nuclear emission of Cen A.

2. Description of the model

We adopt an Eddington mass accretion rate onto the supermassive black hole ($M \sim 10^8$ $\mathrm{M}_\odot$) in the heart of Cen A. The kinetic power redirected to the jets is taken to be a fraction of the accreted one: $L_\mathrm{j} \sim 0.1\dot{M}_\mathrm{acc}c^2$, in accordance with the jet/disc symbiosis hypothesis[11]. A small fraction $q_\mathrm{rel} \sim 0.1$ of that is assumed to go to relativistic particles within a compact cilindrical region close to the base of the jet, where the particles are accelerated in a sort of nozzle[8]. We have fixed that region between $z_0 = 50\,R_g$ and $z_f = 5\,z_0$. The proton to electron luminosity ratio is taken $a = L_p^\mathrm{rel}/L_e^\mathrm{rel} \approx 100$, which implies a proton dominated jet. The injection distribution (particles per unit of energy, volume and time) is assumed to follow $Q_{e,p}(E) \propto E^{-2}$ for the relativistic particles. Most of the jet content is in the form of a mildly relativistic plasma with bulk Lorentz factor that we assume to be $\Gamma = 3$. We consider the kinetic energy of this plasma to be roughly in equipartition with that of a tangled magnetic field $B_0 \sim 10^4$ G.

We have considered that the particle acceleration proceeds with an efficiency η. In the acceleration region the synchrotron losses determine the cut-off in the energy distribution of primary particles, $E_{e,p}^\mathrm{max}$. At heights $z > z_f$ the relativistic particles cool rapidly. If the steepening in the MeV-GeV spectrum of Cen A is considered as the cut-off signature of proton synchrotron radiation, since the magnetic field is fixed we obtain a value $\eta \simeq 10^{-4}$ (Ref. 12 for details). The remainig free parameter, the minimum energy of the injected particles that enters into the normalization of Q, was used to match the MeV luminosity inferred from CGRO. It resulted

$\gamma_{\rm min} \sim 100$.

We have obtained the equilibrium solution of the kinetic equations[13] for the different species of particles (primary p, primary and secondary e that result from charged pion decay and those formed in the internal absorption of VHE photons) taking into account adiabatic and radiative energy losses and the possible escape of the particles from the acceleration region at a time-scale $\sim(z_f - z_0)/c$. Diffusion and convection effects were neglected in our treatment. After computing the energy distribution of the particles, we have calculated the radiative outcome from the most relevant processes. As for the values assumed the Doppler factor is small, we have taken $D \simeq 1$ so luminosities that were calculated in the jet reference frame (RF) are not boosted in the laboratory RF.

The proton synchrotron radiation is the dominant contribution at MeV-GeV energies. Hadronic collisions with the cold material of the jet produce, through π^0 decays, gamma-rays in the 1 GeV- 10 TeV range. The computed luminosity is similar to the proton synchrotron one. The primary leptonic synchrotron contribution results of minor relevance, whereas the IC and Bremsstrahlung from primary and secondary electrons are negligible.

At energies above ~1 GeV significant absorption modifies the production spectrum. In our model the proton synchrotron component extends down to optical wavelengths and provides a dense radiation field which absorbs almost the whole π_0 decay contribution. At the same time it becomes a suitable target for photo-pion production, although the $p\gamma$ contribution to the final SED is negligible. The internal photon-photon absorption leads to the injection of relativistic secondary pairs with energies higher than those of the primary leptons. We consider them together with the leptons that result from the decay of charged pions. The development of IC electromagnetic cascades inside the jets is prevented by the large magnetic field, because the secondaries are mainly cooled by the synchrotron mechanism[14].

In the vicinity of the compact γ-ray production region, the external photon fields provided by the accretion disc and the corona[a] absorb the emerging photons at energies greater than $\sim$ 100 MeV. To compute this effect we have considered that the accretion disc can be represented by the standard geometrically thin, optically thick, Shakura & Sunyaev model. We have fixed the disc extention from $R_{\rm in} = 6R_g$ to $R_{\rm out} = 30R_g$. The corona is modeled as a sphere with $R_{\rm cor} = 8R_g$, emitting photons with spectral index $\alpha = 1.9$, and with lower and higher cutoffs at 1 eV and 20 keV, respectivelly. Geometrical considerations in the calculation of the op-

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[a] Note that because of the absorbing dust lane crossing Cen A central region we lack of information concerning these photon fields. We are assuming a standard description here. See the discussion in the next section.

tical depths τ are relevant to shape the detectable spectrum. We have followed the treatment given by Ref. 15 to compute the opacity provided by the disc photons, and adapted the one from Ref. 16 for the corona. The Figure 1 shows the computed optical depths of the internal and external fields, and the absorbed SED, along with the produced one, are shown in Figure 2. The strong absorption by the corona field dominates over that of the accretion disk (the attenuation factor $e^{-\tau} \sim 0$ for $\tau \gg 1$, insensitive to the actual value of τ).

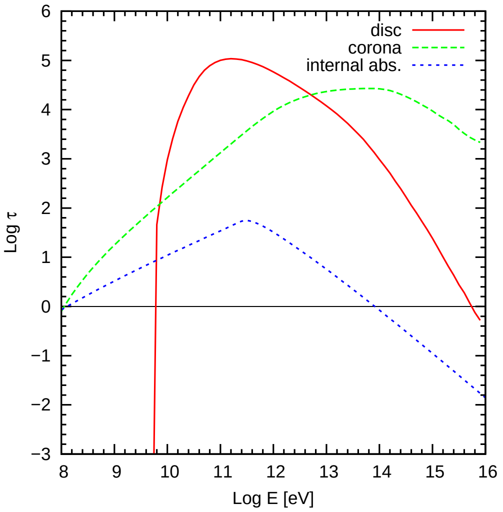

Fig. 1. Computed optical depths, for internal absorption in the radiative field dominated by the proton synchrotron component, and for external fields taken as the sum of the terms due to the accretion disc and the corona.

3. Discussion

The observed features of the high-energy SED (CGRO-range) of Cen A can be reproduced by the simplified model presented here, as coming from a compact acceleration region close to the base of its jets. The low-energy component of the SED (not shown) that is usually attributed to the core of Cen A can result from the radiation of electrons injected in outer regions of the jets, where the magnetic field is lower. Such electrons plus "fresh" hadrons could be injected by the decay of neutrons which travel from the acceleration region without suffering synchrotron losses[17]. Additionally, energetic protons that could escape and/or are convected away in the jet from the acceleration region up to at least a few tens of parsecs, despite of the cooling they suffer, have still enough energy to undergo hadronic interactions, and potentially enlarge the volume of the gamma-ray emitter, to include regions where the external absorption is small. The treatment of convection in such a context is outside the scopes of this work, but is yet an open possibility to explain the TeV emission detected by HESS[18]. It should be emphasized that the Fermi and HESS observations are not simultaneous with those of the CGRO instruments, nor the angular resolution of those instruments is the same. For a phenomenological/parametric model like the one presented here, strong variations on the SED can result from specific conditions, as in particular the emitter size and the accretion/ejection power. Therefore, the VHE SED of Cen A may still be reproduced by a one-zone/multiple-zones models which will bring some initial insight for future more realistic models.

According to our results and as Ref. 14 have pointed out, the absorption of VHE photons at the base of AGN jets is an important problem for the escape of γ-radiation from the production region. For the thoretical models, this absorption can lead to the formation of spectra with almost arbitrary slope in the TeV range. That seems to be unavoidable in the case of Cen A since the external fields are essentially unknown as the core emission is mostly enclosed by the host galaxy.

Finally, if the strength of the magnetic field outside the jets is low enough, the development of IC electromagnetic cascades can become very relevant given the huge thickness of the radiation fields. Then the power contained in the photons with energy $\leq 10^{14}$ TeV that emerge from the jet can be reprocessed to lower energy photons with a rather soft spectrum, and the SED presented here should be

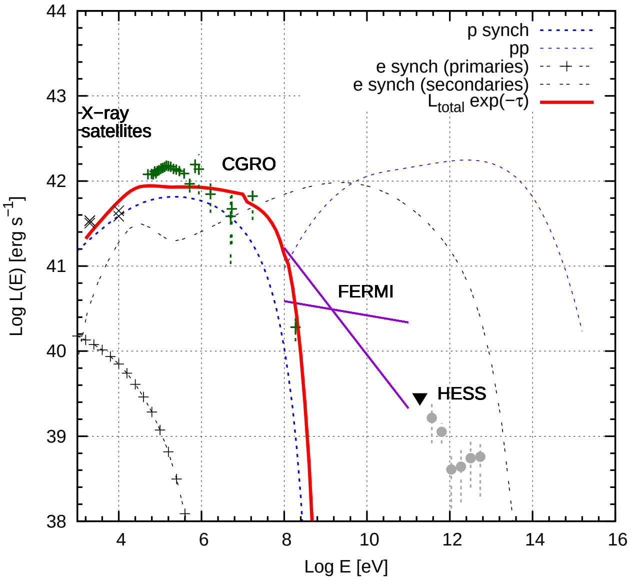

Fig. 2. Computed spectral energy distribution for the inner region of Cen A. At lower energies strong absorption by the dust lane, hiding the AGN core, prevents of testing a model for the optical emission. The high-energy observational constraints are also shown, including: the CGRO measurements (detailed in Ref. 2), the Fermi ones[3], and those by HESS (Ref. 5, which also show the previous upper limits at VHE). The data points correspond to the core of the source.

taken as a lower estimate for energies $E_\gamma \geq 1$ GeV. See Ref. 19 for simulations of electromagnetic cascades in the field of the accretion disc of Cen A.

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