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Sub-parsec and parsec VHE emission from the core of LLAGNs

J. C. Rodríguez-Ramírez*

E-mail: juan.rodriguez@iag.usp.br

E. M. de Gouveia Dal Pino

E-mail: dalpino@iag.usp.br

R. Alves Batista

E-mail: rafael.ab@usp.br

Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo (IAG-USP).
R. do Matão, 1226, 05508-090, Cidade Universitária, São Paulo-SP Brasil.

Radio galaxies with misaligned outflows emit radiation in the very-high-energy regime (VHE; >100 GeV). The standard synchrotron self-Compton scenario is not able to explain this emission. Alternative pictures to explain the production of VHE fluxes could be found in hadronic emission models. Here we consider cosmic-ray (CR) acceleration by magnetic reconnection in the immediate vicinity of the black hole engine and calculate the resulting hadronic emission at sub-parsec, and parsec scales. The former takes place basically due to the interaction of CRs with the inner accretion flow. The latter is due to CRs that escape their acceleration zone and diffuse within the dense interstellar medium at parsec scales. We constrain the power of CR injection by the available magnetic reconnection power of the system and apply this hadronic multi-scale emission scenario to model the VHE spectral energy distribution (SED) from core of Centaurus A. We find that the required CR power needed to explain the VHE cannot be provided only by magnetic reconnection power. On the other hand, CRs produced by magnetic reconnection together with CR injected by supernovae (SNe) during the past 10^4 yr could explain most of the VHE SED assuming a rate of 10^{-2} yr^{-1} SN events within the circumnuclear disc of this radiogalaxy.

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*Speaker.

1. Introduction

The misaligned nature of the outflows in non-blazar AGNs offers a different perspective from that of blazar-like sources for studying high energy radiative processes. Particularly, the radio galaxies Centaurus A (Cen A), NGC 1275, IC 310, PKS 0625-35, M87 and 3C 264 have been detected in the very-high-energy (VHE; > 100 GeV) energy regime (see a review in [1]), which suggests these sources as potential cosmic-ray (CR) accelerators and multi-messenger (MM) emitters. However, the angular resolution and energy sensitivity of current imaging atmospheric Cherenkov telescopes (IACTs) are not able to establish the nature of the VHE emission from radio galaxies.

In this contribution we focus on the origin of the VHE emission of Cen A, which is the nearest and radiogalaxy emitting in VHE bands. The spectrum of the core of Cen A hardens at GeV energies, suggestive of a new gamma-ray emitting component [2] different from the one producing the radio to GeV emission typically modelled with synchrotron self-Compton (SSC) emission in the subparsec jet. The VHE component of Cen A has been investigated with jet models considering leptonic emission produced in the kpc knots of the outflows [3], as well as with jet hadronic and two-zone lepto-hadronic scenarios ([4],[5]). In this talk, we focus on the potential contribution to the VHE spectrum of Cen A, of radiation produced black hole (BH) accretion flow region [6, 7] and the circumnuclear disc (CND) of Cen A [8].

Regarding γ rays of hadronic origin in the nuclear region of Cen A, CR acceleration in the accretion flow of the central engine is a potential driving mechanism. In cold and thin accretion discs, particle acceleration could be triggered by turbulent magnetic reconnection events [9, 10, 11] in the magnetised coronal region [6]. Alternatively, turbulent magnetic reconnection acceleration could also occur in advetion-dominated accretion flows [12] (ADAFs, which are appropriate models for BHs with mass accretion rates $< 10^{-3}\dot{M}_{Edd}$) and further stochastic processes could accelerate CRs up to tens of PeVs [13].

For the case of CR accelerated in the immediate vicinity of the central black hole of radiogalaxies, the emission of the escaping CRs can take place at distances of different scales from the acceleration region. In Figure 1, we show images at different scales around the nuclear region of the radio galaxy Cen A. Figure 1a depicts a model for the gas density of the BH accretion plasma in the central 10^{-4} pc of Cen A, obtained with the GRMHD `harm` code ([14], see also [15] and references there in). Figure 1b displays a toy model for the gas density within the inner 80 pc of the CND. Figure 1c, shows an observed molecular line emission map of the central kpc region of Cen A, which encloses the whole CND and the central part of the dust lane. Finally, Figure 1d is a composite image of the whole radio galaxy.

In a previous work [7], we investigated the possible VHE emission produced in the central $100R_g \sim 10^{-4}$pc of the radiogalaxy Cen A, assuming CR acceleration by magnetic reconnection within a hot and thick accretion flow. We found that the VHE produced in the BH accretion flow of Cen A can partially explain the VHE excess detected from this radiogalaxy. Here we model the emission produced by the CRs that escape their acceleration zone (the inner 100 R_g) and then diffuse within the surrounding interstellar medium at pc scales. The environment of Cen A at $\sim$ 100 pc from the central engine is conformed by the circumnuclear disc (CND, [18]). Thus here we explore the potential VHE gamma-ray fluxes produced due to proton-proton interactions of CRs interacting with the densest regions of the CND.

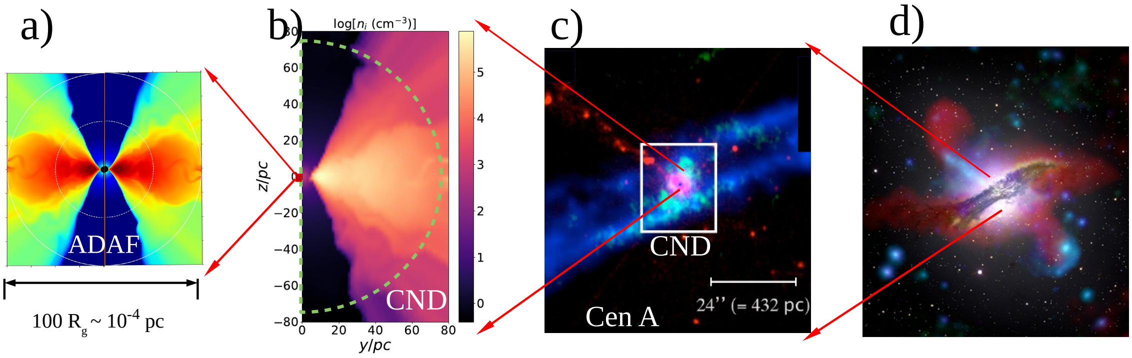

Figure 1: a) General relativistic advection-dominated accretion flow model for the BH accretion flow of Cen A in the region of the central $\sim 100\ R_g$. b) Toy model of the 80 kpc inner region of the CND of Cen A. The green, dashed semi-circle represents the spherical boundary where we collect the particles and photons produced in our Monte Carlo CR simulations (see the text). c) Composite image of the central 1kpc of Cen A [16]. The CND is located within the white rectangle. d) Composite image of the whole radio galaxy Cen A [17].

In the next section, we briefly summarise our previous results on hadronic VHE emission produced in the BH accretion flow in the central $\sim 10^{-4}$ pc. Then we describe the observed characteristics of the CND where we simulate the interaction of the CRs that escape the subparsec acceleration zone. In Section 3, we describe the Monte Carlo (MC) approach that we employ to calculate the CR emission and present SED models. Finally, we discuss and summarise our results in Section 4.

2. The BH accretion flow and the CND environments

In a previous contribution [7], we simulated CR emission produced within the BH accretion flow located in the central 100 $R_g \sim 10^{-4}$pc of Cen A. To do this, we assumed an accretion rate of 10^{-3} $M_\odot$ yr^{-1} onto the BH of Cen A [19] and considered CR accelerated by magnetic reconnection in the magnetised accretion flow [9, 12]. To calculate the resulting CR emission we combined three numerical techniques (similarly to the study of VHE emission from the Centre of our Galaxy in [15]).

We first modelled the accretion plasma as a radiative inefficient accretion flow (RIAF) employing the general relativistic magnetohydrodynamics (GRMHD) `harm` code [14] (see Figure 1a), and we modelled internal photon field with leptonic radiative transfer employing the `grmonty` code [20]. To calculate the emission and absorption of γ-rays we injected CRs and simulated their interactions with the accretion flow environment employing the `CRPropa 3` code [21]. In these CR simulations we considered γ-rays produced by proton-proton interactions, photo-pion production as well as electromagnetic cascades due to γ-γ pair production and inverse Compton (IC) scattering. For a CR injection consistent with the magnetic reconnection power of the system (i.e., CR injection power representing a fraction of the magnetic reconnection power), the resulting gamma-rays that leave the accretion flow region are able to explain the spectrum of Cen A only for energies $<$ 1 TeV. The γ-ray emission at highier energies is suppressed byγ-γ pair productions due to the internal photon field. This can be seen in the blue curve labelled as model m_3 in Figure 4 of [7], which we reproduce in Figure 2 of this Proceeding with the label "RIAF hadronic". For this model, the power of the CRs that escape the accretion flow zone is $W_{esc} = 2 \times 10^{40}$ erg s^{-1}.

In the present contribution, we consider the CRs that escape the accretion flow zone (the central $\sim 10^{-4}$ pc) of our previous study and simulate their propagation in the interstellar medium within the central 75 pc. This region is conformed by the inner part of the (CND) of CenA, which is a gaseous rotating structure observed with a projected size of $\sim$200$\times$400 pc with gas density values of $n = 10^{3-5}$ cm^{-3} [18].

Here we assume that the densest part of the CND lies in the central 75 pc of Cen A, where we simulate the propagation and emission of CRs. As a first approximation we model the gas density profile of the CND with one of the gas density profiles obtained in our previous study of the BH accretion at subparsec scales and re-scale it to a radius of 80 pc. We normalise the density stratification for this CND model with a maximum gas density of $n = 5 \times 10^5$ cm^{-3} (see Figure 1b). Within this CND torus model we implement a magnetic field with a purely toroidal component that follows the gas density profile as $B_\phi \propto n$, normalised with $B_\phi = 100\mu$G at $n = 10^4$ cm^{-3}. Here we assume that the radio to GeV SED components are produced by SSC radiation in the inner subparsec jet [22], and thus its radiation field is negligible to attenuate gamma-rays beams produced in the CND along our line of sight. We consider, on the other hand, the starlight radiation field ([23]) as the principal attenuating field for VHE photons.

3. MC simulations of CR emission in the CND

We inject CRs as a central point source and simulate their propagation within the central 75 pc of the CND, employing the background gas density and magnetic field described in the previous section. This central CR point-like injection represents the CRs that escape the acceleration zone from subparsec scales, where we assume CR acceleration by magnetic reconnection in the BH accretion flow (see the previous section and [7]). The injection of CRs is modelled assuming a constant CR power W_{esc} during the previous 10^4 yr, with a stationary power-law spectrum $\propto E^{-p}\exp\{-E/E_{max}\}$. Thus, a particular emission model is determined by defining the values of the parameters W_{esc}, p, and E_{max} of CR injection. Within this picture, the resulting γ-ray fluxes have a stable behaviour, which is compatible with the lack of variability of the H.E.S.S. and *Fermi*-LAT data of Cen A [2]. The SEDs of CR emission (γ-rays and neutrinos) are built by considering a time window interval Δt_w of the last 10^3 yr. Thus, during this time window interval we allow for emission of CRs injected from 10^4 yr to the present time.

To perform this CR simulation, we employ the MC `CRPropa 3` code [21]. To mimic a continuous CR injection during 10^4 yr, we run 10 simulations with burst-like CR injection each one with identical injection energy of $E_{inj} = W_{esc}10^3$ yr, but with the maximum evolution times of $t_{max} = 10^3$, 2×10^3, ... , 9×10^4, and 10^4 yr. Thus, to build the SED within the time window interval Δt_w, we only consider the CR emission produced during the last 10^3 yr in each one of these simulations. We consider proton-proton as the only channel for γ-ray and neutrino production (photo-pion interactions are relevant for ulta-high-energy cosmic rays, which are not considered here). Synchrotron cooling of the CRs by the background magnetic field is considered, but we do not follow synchrotron photons. In this preliminary study, we do not consider the contribution of

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Table 1: Parameters of the emission profiles plotted in Figures 2 and 3.

Model	W_{esc} $\times 10^{40}$ [erg s^{-1}]	p	ε_{cut} [PeV]
m_1	1.4	1.5	5
m_2	1.4	1.5	0.05
m_3	10	2.5	0.1

electromagnetic cascading to the resulting γ-ray spectra. The effect of γ-rays by pair production is accounted in the calculation of the SEDs considering the γ-γ optical depth due to the starlight photons of Cen A derived by [23]. The break conditions for the particles and photons of the simulations are attained if they cross a spherical boundary of 75 pc, or complete a maximum trajectory of $d_{max} = ct_{max}$, or else they attain a minimum energy of 10^{11} eV.

The cyan, purple and orange curves displayed in Figures 2 and 3 are SED models of γ-rays and neutrinos that result from the simulations described above. These emission models correspond to three different combinations of the parameters W_{esc}, p and E_{max} for CR injection, which are specified in Table 1.

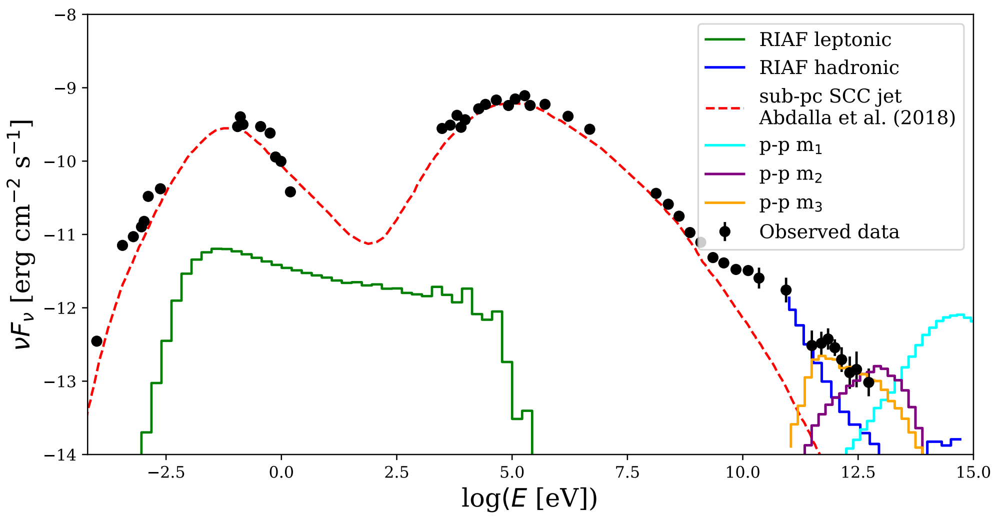

Figure 2: SED of the radio galaxy Cen A. The different curves represetn different emission models described in the text. The radio to MeV data points are adapted from [2] (gamma-rays), [24] and [25] (radio to optical), [26] (18 keV-8 MeV), and [27] (1-30 MeV).

4. Discussion and conclusions

Here we investigate γ-ray fluxes potentially produced by proton-proton interactions of CRs with the densest region of the CND of Cen A. We consider CRs originated by turbulent magnetic reconnection in the immediate accretion flow of the SMBH of Cen A, within the central 10^{-4} pc.

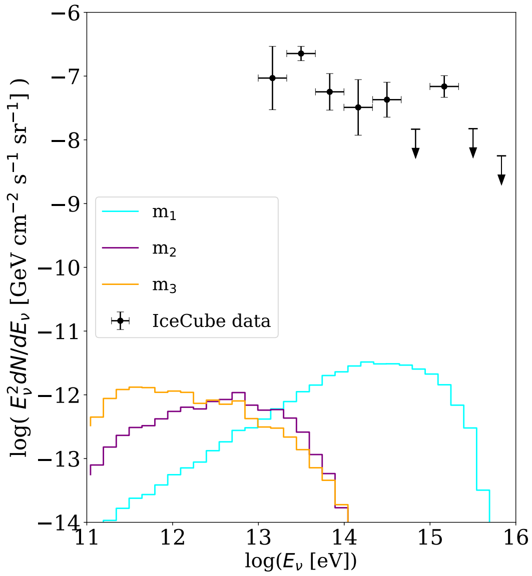

Figure 3: All-flavour neutrino fluxes associated to hadronic emission models of Figure 2. The IceCube high-energy starting events are taken from [28].

For parameters corresponding to Cen A, such CRs can escape the BH accretion zone region with a power of $W_{esc} = 10^{40}$ erg s^{-1} according to our previous study [7].

We assume that the densest region of the CND is located within the central 80 pc, which we model with a torus-like profile with densities of n$\sim 10^{3-5}$ cm^{-3} and a purely toroidal magnetic field of B_ϕ ~0.01 - 1 mG (see Figure 1b and Section 2). Although one could obtain a more realistic model for the CND (with an appropriate magnetohydrodynamical simulation, for instance), the CND toy model presented here provides fiducial optimistic parameters for CR confinement as well as for efficient γ-ray production by proton-proton interactions. Thus, with this target environment model, we here investigate the best possible contribution to the VHE SED of Cen A due to CRs interacting with the CND and injected in the previous 10^4 yr.

The emission models m_1 and m_2 (see Figure 2 and Table 1) are consistent with the power of CRs that escape the BH accretion flow. We see that the emission of these CRs contributes only to the highest energy data points of the SED, if a cut-off energy of 10^{13} eV for CR injection into the CND is assumed (see model m_2). The model m_3 appears to match well the 10^{11-13} eV region of the SED. However, this model requires a power of 10^{41} erg s^{-1} of CRs injected into the CND, which is one order of magnitude larger than the power of CRs that escape the BH accretion flow. Thus, the CRs assumed in this model m_3 are unlikely to have been originated in the BH accretion flow only. Nevertheless, the CR injection total power of this model could be achieved with the contribution of SNe explosions taking place within the central 80 pc of Cen A, with a rate of 10^{-2} yr^{-1} events. The neutrino fluxes associated to any model of gamma-rays produced within the accretion flow zone or at pc scales in the CND do not contribute significantly to the diffuse neutrino emission measured by the IceCube (see Figure 3).

Based on the results discussed here for the γ-rays produced in the BH accretion flow as well as in the CND of Cen A, we conclude that CRs originated in the BH accretion flow (the central 10^{-4} pc) cannot explain the whole VHE SED of Cen A. On the other hand, CRs produced by magnetic reconnection together with CR produced by SNe during the past 10^4 yr could explain most of the VHE SED assuming a rate of 10^{-2} yr of SN events taking place within the CND of Cen A.

The analysis described here is based on the assumption of a steady CR injection at least during the past 10^4 yr. Thus, the multi-scale CR emission model discussed here can be applied to other radiogalaxies displaying relatively stable VHE emission like PKS 0625-354 and 3C 264. Also the analysis presented here could be applied to the quiescent VHE emission component of variable radio galaxies like NGC1275 and M87.

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