Modelling the core emission of Centaurus A: effects of the second SSC photon generation

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in collaboration with S. Dimitrakoudis, L. Eva, A. Mastichiadis
Unification scheme of Urry & Padovani (1990)

INTRO
AGN unification models
Centaurus A

GOALS
Modelling of the core emission

INTERLUDE
Emission processes in leptohadronic models

RESULTS
Photon emission
Neutrino-CR emission

Unification scheme as presented in the 9th Integral Workshop, 2012

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- Closest radio galaxy
  - \( D = 3.8 \pm 0.1 \) Mpc (Harris 2009; review of all existing measurements)

- inclination angle jet/line-of-sight:
  1) \( 73^\circ \pm 3^\circ \) (Graham 1979; H II regions)
  2) \( 60^\circ - 77^\circ \) (Jones et al. 1996; radio brightness ratio jet/counterjet)
  3) \( 50^\circ - 80^\circ \) (Tingay et al. 1998b; radio brightness ratio jet/counterjet; parsec-scale!)
  4) \( \sim 15^\circ \) (Hardcastle et al. 2003b; radiojet/counterjet symmetry and speeds; kiloparsec-scale!)

Figure from Burns et al. 1983

Smoothed 4.57 GHz map of the whole radio structure of Cen A from Alvarez et al. 2000
Recent detections of Cen A at gamma-rays

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The modelling of the core emission tries to answer the following:

- Do blazar emission models apply to the case of Cen A?
- Can the MW core emission be attributed to relativistic electrons only or is it necessary to assume the presence of relativistic protons?

Recent results of PAO triggered the discussion on the possible connection (Pierre Auger Collaboration 2008, 2010a; Gorbunov et al. 2008; Stanev 2008; Moskalenko et al. 2009; Hillas 2009)

- Is Cen A a source of ultra high energy cosmic rays (UHECR) ?
- What are the possible sites of CR acceleration to UHE?
Emission mechanisms of relativistic protons

- Synchrotron radiation
- Proton-photon (Bethe-Heitler) pair production

Bethe–Heitler production

- Proton-proton pion production

Production of relativistic electron/positron pairs → Synchrotron and IC losses

Neutrino emission!
Current status in MW modelling of Cen A's core emission

Leading scenario up to the GeV energies: synchrotron self-Compton (SSC)

The origin of the VHE gamma-ray emission differs between the models

Up right: Sahu et al. 2012, PhRvD, 85
The parameters of the typical SSC model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SSC</th>
<th>Model SSC (Abdo et al. 2010a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (cm)</td>
<td>$4 \times 10^{15}$</td>
<td>$3 \times 10^{15}$</td>
</tr>
<tr>
<td>B (G)</td>
<td>6</td>
<td>6.2</td>
</tr>
<tr>
<td>$\delta$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\gamma_{e,\text{min}}$</td>
<td>$1.3 \times 10^3$</td>
<td>300</td>
</tr>
<tr>
<td>$\gamma_{\text{br}}$</td>
<td>$\gamma_{\text{br}}$</td>
<td>800</td>
</tr>
<tr>
<td>$\gamma_{e,\text{max}}$</td>
<td>$10^6$</td>
<td>$10^8$</td>
</tr>
<tr>
<td>$p_{e,1}$</td>
<td>$-,\text{or},\text{null}$</td>
<td>1.8</td>
</tr>
<tr>
<td>$p_{e,2}$</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>$\ell_{e,\text{inj}}$</td>
<td>$6.3 \times 10^{-3}$</td>
<td>$8 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\ell_{B}$</td>
<td>$4.6 \times 10^{-3}$</td>
<td>$3.7 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Application of SSC model to misaligned blazars should be considered with caution because

Large viewing angle $\rightarrow$ low Doppler factor $\rightarrow$ inefficient boosting of the radiation

$$L_{obs} = \delta^4 L' \propto \delta^4 L_{e,\text{inj}}$$

For $L_{obs}$ high $\rightarrow$ $L_{e,\text{inj}}$ high $\rightarrow$ 2nd SSC component not negligible!
Numerical treatment

2nd SSC peak

Cannot explain the Fermi data!

2nd order scatterings in the Klein-Nishina regime lead to steep spectrum

Analytical treatment

- Solve for the steady state electron distribution (monoenergetic injection, synchrotron and SSC losses)
- Calculate the peak position of the synchrotron, 1st SSC and 2nd SSC components
- Calculate their peak luminosities

\[
\mathcal{L}_{\text{peak}}^{\text{syn}} = \frac{u_b m_e c^3}{4R} \left( -1 + \sqrt{1 + \frac{12\ell_e^{\text{inj}}}{\ell_B}} \right)
\]

Log Flux (erg cm\(^{-2}\) s\(^{-1}\))
1.3e-9

\[
\mathcal{L}_{\text{peak}}^{\text{ssc,1}} = \frac{3\sqrt{3} u_b m_e c^3}{16e} \frac{1}{R} \left( -1 + \sqrt{1 + \frac{12\ell_e^{\text{inj}}}{\ell_B}} \right)^2
\]

ICS between electrons and 1st SSC photons occur mainly in KN regime.
2.2e-9

1 order of magnitude.

\[
\mathcal{L}_{\text{peak}}^{\text{ssc,2}} = \frac{9\sqrt{3} m_e c^3}{64e} \frac{u_b}{b^{1/2} R \gamma_0^{5/2}} \left( -1 + \sqrt{1 + \frac{12\ell_e^{\text{inj}}}{\ell_B}} \right)^3
\]

2.3e-10
If protons are accelerated up to VHE in the core of Cen A...

Target photons for Bethe-Heitler and photo-pion interactions → synchrotron & 1st generation SSC photons

If protons are accelerated up to VHE in the core of Cen A...

Target photons for Bethe-Heitler and photo-pion interactions → synchrotron & 1st generation SSC photons

### Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model 1</th>
<th>Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ (cm)</td>
<td>$4 \times 10^{15}$</td>
<td>$2.2 \times 10^{16}$</td>
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<tr>
<td>$B$ (G)</td>
<td>6</td>
<td>3.5</td>
</tr>
<tr>
<td>$t_{cr}$</td>
<td>$1.3 \times 10^5$ s</td>
<td>$7.3 \times 10^4$ s</td>
</tr>
<tr>
<td>$\delta$</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>$\theta$</td>
<td>$35^\circ$</td>
<td>$20^\circ$</td>
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<tr>
<td>$t_{e,esc}/t_{cr}$</td>
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<td>4</td>
</tr>
<tr>
<td>$\gamma_{e,min}$</td>
<td>$1.3 \times 10^3$</td>
<td>$1.3 \times 10^3$</td>
</tr>
<tr>
<td>$\gamma_{e,max}$</td>
<td>$10^6$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$p_e$</td>
<td>4.3</td>
<td>4.5</td>
</tr>
<tr>
<td>$f_{\text{inj}}^{(\text{c})}$</td>
<td>$6.3 \times 10^{-3}$</td>
<td>$7.9 \times 10^{-4}$</td>
</tr>
<tr>
<td>$t_{p,esc}/t_{cr}$</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>$\gamma_{p,min}$</td>
<td>$2 \times 10^7$</td>
<td>$2 \times 10^7$</td>
</tr>
<tr>
<td>$\gamma_{p,max}$</td>
<td>$1.8 \times 10^9$</td>
<td>$1.8 \times 10^9$</td>
</tr>
<tr>
<td>$p_p$</td>
<td>4.3</td>
<td>4.5</td>
</tr>
<tr>
<td>$f_{\text{inj}}^{(\text{c})}$</td>
<td>$4 \times 10^{-6}$</td>
<td>$7.9 \times 10^{-7}$</td>
</tr>
<tr>
<td>$u_r$ (erg/cm$^3$)</td>
<td>12.3</td>
<td>2.6</td>
</tr>
<tr>
<td>$u_e$ (erg/cm$^3$)</td>
<td>1.9</td>
<td>2.3</td>
</tr>
<tr>
<td>$u_p$ (erg/cm$^3$)</td>
<td>6.8</td>
<td>15.4</td>
</tr>
<tr>
<td>$u_B$ (erg/cm$^3$)</td>
<td>1.4</td>
<td>0.5</td>
</tr>
<tr>
<td>$L_e^{\text{inj}}$ (erg/s)</td>
<td>$1.2 \times 10^{43}$</td>
<td>$1.3 \times 10^{43}$</td>
</tr>
<tr>
<td>$L_p^{\text{inj}}$ (erg/s)</td>
<td>$1.4 \times 10^{43}$</td>
<td>$2.4 \times 10^{43}$</td>
</tr>
<tr>
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<td>$2.5 \times 10^{43}$</td>
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</tr>
</tbody>
</table>

**Prediction:** TeV variability is not expected

**Reason:** Significant $\gamma\gamma$ absorption above $10^{26}$ Hz
Neutrino and HE CR spectra of the leptohadronic models

HE neutrons escape the emitting region → HE protons
(e.g. Kirk & Mastichiadis 1989; Begelman 1990; Atoyan & Dermer 2003)

Upper limit of HE proton flux arriving at earth as obtained in our models

If Cen A is the source of the UHECR excess observed by PAO, then there must be other acceleration site of CR than the core!
Summary

- According to the unification model of AGN, gamma-ray radio loud galaxies are considered misaligned blazars.

- The Doppler factor $\sim 1-3$ for misaligned blazars in contrast to blazars where the inferred values can be as high as 20-30.

- If the gamma-ray emitting region of a misaligned blazar is compact and the observed luminosity high, higher SSC photon generations are not negligible.

- In the case of Cen A's core emission, the emergence of the 2nd SSC component destroys the fit of the SED in the Fermi energy band.

- Addition of a relativistic proton distribution successfully explains both the GeV and TeV emission from the core.

- The neutrino efficiency is extremely small.

- The HE proton distribution cannot account for the UHECR excess observed by PAO in the direction of Cen A.

- The core of Cen A cannot be the acceleration site of UHECR.