The BL Lac heart of Centaurus A

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ABSTRACT

Emission from the nucleus of the closest radio galaxy, Centaurus A, is observed from the radio to the gamma ray band. We build, for the first time, its overall Spectral Energy Distribution (SED) that appears to be intriguingly similar to those of blazars, showing two broad peaks located in the far-infrared band and at \(\sim 0.1\) MeV respectively. The whole nuclear emission of Centaurus A is successfully reproduced with a synchrotron self-Compton model. The estimated physical parameters of the emitting source are similar to those of BL Lacs, except for a much smaller beaming factor, as qualitatively expected when a relativistic jet is orientated at a large angle to the line of sight. These results represent strong evidence that Centaurus A is indeed a misoriented BL Lac and provide strong support in favour of the unification scheme for low luminosity radio-loud AGNs. Modeling of the SED of Centaurus A also provides further and independent indications of the presence of velocity structures in sub-pc scale jets.

Key words: Galaxies: active – galaxies: jets – galaxies: nuclei – radiation mechanisms: non-thermal – BL Lacertae objects: general

1 INTRODUCTION

Unification models for radio-loud active galactic nuclei (AGN) are usually tested by comparing the extended properties (e.g. radio and optical emission, environment) of the beamed sources and their putative parent population. Clearly, more compelling results could be obtained by directly considering the nuclear AGN emission.

The optical nuclear emission has been recently identified in FR I radio-galaxies through HST observations of a complete subsample of 3CR sources (Chiaberge, Capetti & Celotti 1999). The presence of a strong correlation between radio and optical emission provides a straightforward indication of a direct association between radio cores and the faint central compact cores observed by HST, arguing for a common non-thermal synchrotron origin of both components. This discovery, by itself, provides qualitative support for the low-luminosity radio loud AGN unification models (Barthel 1989; Urry & Padovani 1995 for a review). In fact, in the frame of the unification schemes, the non-thermal beam emission which dominates in blazars, should also be present in radio galaxies, although strongly de-amplified.

Nonetheless, a more quantitative analysis showed that cores of radio galaxies are largely over-luminous with respect to what is expected from mis-oriented BL Lac jets, for typical values of the bulk Lorentz factor (Chiaberge et al. 2000). In order to reconcile this result with the unification scheme, velocity structures in the jet have been suggested, where a fast spine is surrounded by a slower (but still relativistic) layer.

Modeling of SED could provide an even more stringent test for the unified scheme, as it represents a fundamental tool for obtaining information on the physical conditions of the emitting region, as it is usually done for blazars (e.g. Ghisellini et al. 1998). Unfortunately, the nuclear SED of radio-galaxies are in general not sufficiently well sampled to follow directly this approach. More information on their nuclear emission, in addition to the radio and optical data, comes from X-ray observations, but the available data are still unsuit to deriving strong constraints (see e.g. Capetti et al. 2000).

However, there is one radio-galaxy for which a sufficiently large set of photometric data is available to build a well sampled SED: the nearest radio galaxy Centaurus A. The presence of an AGN in Centaurus A is evident from the radio through the \(\gamma\)-ray band, as detailed in the following section. In this Letter we take advantage of this broad band energy coverage to gain a better understanding of the nature of the nuclear emission of Centaurus A. The paper is structured as follows: in Sect. 2 we build the nuclear SED, which is modeled in the frame of a pure synchrotron self-Compton scenario in Sect. 3; finally, in Sect. 4 we examine and discuss our findings in the light of the unification schemes.
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We adopt a distance to Centaurus A of 3.5 Mpc (Hui et al. 1993).

2 THE NUCLEAR SPECTRAL ENERGY DISTRIBUTION

In order to build the overall nuclear SED of Centaurus A, we collected from the literature the nuclear fluxes spanning the widest range of frequencies, from the radio to the gamma-ray band.

Starting from the highest energies, Centaurus A is at present the only radio galaxy detected in the \( \gamma \)-ray band by CGRO. When it was observed for two weeks in 1991, during an intermediate state of activity, the spectra obtained by OSSE and COMPTEL (and the EGRET flux) appear to be smoothly connected, forming a well defined emission peak at \( \sim 0.1 \) MeV, in a \( \log(\nu F_\nu) \) vs \( \log \nu \) representation (Steinle et al. 1998). These are the only published simultaneous data in such bands. In the X-ray band an absorbed \( \left(N_H \sim 10^{23} \text{ cm}^{-2}\right) \) power-law component with energy index \( \alpha \sim 0.7 - 0.9 \) \( (F_\nu \propto \nu^{-\alpha}) \) has been detected by both RXTE and BeppoSAX (MECS+PDS data are reported here) (Rothschild et al. 1999, Grandi et al. 2000). The X-ray flux is also variable (more than a factor of 4) on timescales of a few hours. A significant improvement in our knowledge of the low energy part of the spectrum (mm-optical) has been made thanks to HST, ISOCAM and SCUBA observations. In particular, the near-IR nuclear component is clearly seen during an intermediate state of activity, the spectra obtained thanks to HST, ISOCAM and SCUBA observations.

The radio band is covered by VLA (Burns et al. 1983) and VLBI (Tingay et al. 1998) observations.

These data produce the observed SED shown in Fig. 1 in a \( \log(\nu L(\nu)) - \log \nu \) representation. The SED appears to be composed by two broad peaks: the low energy one reaching its maximum in the far-IR, between \( 10^{12} \) and \( 10^{13} \) Hz and the high energy one with a well defined maximum at about \( 0.1 \) MeV. As both maxima occur in spectral bands essentially unaffected by dust/gas absorption, the double-peaked shape is well established regardless of extinction. The SED of Centaurus A thus intriguingly resembles that of blazars and indeed (qualitatively) what expected in a misaligned BL Lac object. In fact, according to the unified scenarios for jetted AGN, the counterpart of Centaurus A when seen at small angle with the jet axis should appear as a BL Lac. This represents a strong clue that Centaurus A nuclear emission might be interpreted by analogy with blazars, whose low energy peak is attributed to non-thermal synchrotron emission and the high energy one to inverse Compton scattering of softer photons.

We will explore this possibility in the next section, modeling the observed SED in order to obtain information on the physical parameters of the source.

![Figure 1. The observed spectral energy distribution of the nucleus of Centaurus A (see text).](image)

3 THE SYNCHROTRON SELF-COMPTON SCENARIO

The SED of blazars is interpreted as due to synchrotron and inverse Compton emission. In this frame, there are two main possibilities for the nature of the soft photons which are scattered to high energies: this radiation field can be either internal to the source, i.e. the synchrotron emission itself (synchrotron self-Compton, SSC, Maraschi, Ghisellini & Celotti 1992, Bloom & Marscher 1993) or external, e.g. photons emitted by either the accretion disc or the Broad Line Region (Dermer & Schlickeiser 1993, Sikora, Begelman, Rees 1994, Ghisellini & Madau 1996). For the lowest luminosity blazars (i.e. BL Lacs) the contribution of the external photon field is probably small (Ghisellini et al. 1998). In fact the lack of strong broad emission lines (Marconi et al. 2001 for Centaurus A), disc and dust emission in their spectra are typical of these sources and argues against substantial photons fields external to the jet. This suggests the interpretation of the observed nuclear emission as pure SSC radiation from the BL Lac heart of Centaurus A.

3.1 The model

The simplest representation of the source is a spherical homogeneous region, embedded in a tangled magnetic field. Relativistic electrons are continuously injected at a rate \( Q(\gamma) \left[ \text{cm}^{-3} \text{s}^{-1} \right] \propto \gamma^{-\beta} \) between \( \gamma_{\text{min}} \) and \( \gamma_{\text{max}} \) (\( \gamma \) being the Lorentz factor), and they loose their energy radiatively. In this scenario, the free parameters of the model are: the size of the source \( R \), the magnetic field \( B \), the injected luminosity \( L_{\text{inj}} \), the relativistic beaming factor \( \delta = \left[ 1 - \beta \cos \theta \right]^{-1} \) (where \( \theta \) is the angle between the jet axis and the line of sight), \( \gamma_{\text{min}}, \gamma_{\text{max}} \) and the slope \( p \). The resulting electron distribution at equilibrium is a broken power-law. For de-
The minimum variability time scale of $\gamma$ from the OSSE observations (Kinzer et al. 1995), although shorter than the values of $B$ which can be directly compared with the observations.

For the prominent kpc-scale dust lane of Centaurus A that causes the main effect of this procedure is to substantially reduce the depth of the SED minimum at $\nu \sim 10^{15}$ Hz, as can be seen in the corresponding corrected SED presented in Fig. 2.

A more accurate approach is to obtain the equilibrium solution of the continuity equation which governs the temporal evolution of the emitting electron distribution $N(\gamma, t)$, also taking into account the effects of the Klein-Nishina decline and the possible escape of particles from the source on a timescale $t_{\text{esc}}$:

$$\frac{\partial N(\gamma, t)}{\partial t} = \frac{\partial}{\partial \gamma} \left[ \frac{\gamma}{\gamma \nu_e} N(\gamma, t) \right] + Q(\gamma, t) - \frac{N(\gamma, t)}{t_{\text{esc}}} = 0$$

where $\dot{\gamma} = \gamma_0 + \gamma_C$ is the total (synchrotron + self-Compton) cooling rate. We solve the equation numerically using the code extensively described by Chiaberge & Ghisellini (1999), which also calculates the spectrum emitted by the resulting electron distribution. A significant advantage of this method is that it produces a continuous representation of the SED which can be directly compared with the observations.

Before proceeding, we must consider the effects of the prominent kpc-scale dust lane of Centaurus A that causes significant extinction, particularly in the optical and near-IR bands. Marconi et al. (2000) found color excesses as high as E(B-V) ~ 2.5 in the circumnuclear regions which can be considered as a lower limit to the nuclear absorption. We thus de-reddened the observed data points using $A_V \sim 8$ and adopting the reddening law of Cardelli et al. (1989).

The overall agreement between model and data is quite remarkable. The “fit” to the SED of Centaurus A obtained with the SSC model is represented as the dashed line in the same Fig. and the corresponding model parameters are listed in Table 1. We point out that the optical core luminosity predicted by the radio-optical core flux correlation for FR I found by Chiaberge et al. (1999).

### 4 DISCUSSION

All of the physical parameters inferred from the model (see Table 1) are in the range spanned by blazars (e.g. Ghisellini et al. 1998), except for the beaming factor, which is significantly lower. A smaller amount of beaming is indeed qualitatively expected in the frame of the unification schemes for AGN, as radio galaxies are believed to be observed at angles with the jet axis larger than blazars. In the case of Centaurus A, this is directly confirmed by VLBI observations which, in order to account for the observed jet-counterjet ratio, imply an angle between 50° and 80° (Tingay et al. 1998). The fact...
Table 1. Model parameters for the SED of Centaurus A

| Parameter | Value |
|-----------|-------|
| $R$       | $1.2 \times 10^{16}$ cm |
| $B$       | $0.5$ G |
| $\delta$  | 1.2 |
| $L_{inj}$ | $2.7 \times 10^{42}$ erg s$^{-1}$ |

$L_{inj}$ is the injected power (in particles of energy equal to $\gamma m_{\text{e}}c^2$).

that nuclear emission of Centaurus A can be successfully modeled as SSC radiation with physical parameters consistent with those used for BL Lacs and a lower value of $\delta$ provides evidence that the source is indeed a misoriented BL Lac and thus supports the unification scheme for low luminosity radio-loud AGNs.

However the bulk Lorentz factors inferred for BL Lacs are typically in the range $\Gamma \sim 15 - 20$. For such a $\Gamma$, at the inferred angles of sight, an even lower value of $\delta$ would be expected. More quantitatively, for the above range of viewing angles, such velocities imply a $\delta$ factor between 0.18 and 0.06, which are incompatible with the values found from the (analytic and model fitting) estimates. On the other hand the SSC model strongly constrains the value of $\delta$, as it depends only on parameters which are observationally well determined: i) the variability timescale (a value lower than the assumed one would result in a higher $\delta$); ii) the position and (weakly) the luminosity of the emission peaks, which are well defined unless (unobserved) dramatic variability has affected the measurements (variations by a factor of $\sim 4$ of do not significantly change $\delta$). From the analytic relations reported in Sect. 3.4 it turns out that it cannot be significantly smaller than $\sim 1$. Furthermore, based purely on geometrical considerations, at large viewing angles the beaming factor cannot be higher than $\delta \sim 1.3$ (even for $\theta = 50^\circ$ and independently on the value of $\Gamma$). The highest value of $\delta$ is reached for $\Gamma \sim 1$ while for higher Lorentz factors $\delta$ rapidly decreases. Therefore, our results constrain the Doppler factor of the observed region to be $\delta \sim 1$ and this in turn sets an upper bound to the Lorentz factor, $\Gamma \lesssim 3 - 5$. These values are consistent with the mildly relativistic proper motions observed on sub pc-scales (Tingay et al. 1998).

As already discussed in the Introduction, Chiaberge et al. (2000) found a similar indication that the emission in FR I cores is not quantitatively compatible with being mis-oriented high Lorentz factor ($\Gamma \sim 15 - 20$) BL Lac jets. In fact, cores of radio galaxies are overluminous (both in the optical and radio band) by factors 10 -- 10$^5$ with respect to the predictions of a “one velocity beaming model” for BL Lacs with similar extended radio power. Within the unification scenario the simplest and rather plausible hypothesis to account for such discrepancy is to assume a structure in the jet velocity field in which a fast spine is surrounded by a slow layer. The slower component has still to be relativistic and we found that for $\Gamma_{\text{layer}} \sim 2$ we can account for the unification of FR I cores and BL Lacs. The observed emission in aligned objects would then originate mostly from the jet spine, while in the misaligned ones would be dominated by emission from the slower layer. In this hypothesis, the radiation observed from the nucleus of Centaurus A can be identified with emission from the jet layer. Modeling the SED of Centaurus A thus provides an independent indication of the presence of velocity distribution in sub-pc scales jets.

4.1 Centaurus A and the blazar sequence

The population of blazars shows a link between the overall spectral properties and the nuclear radio luminosity (Fossati et al. 1998, Ghisellini et al. 1998): an increase in the nuclear radio luminosity (at 5 GHz) corresponds to an increase in the bolometric luminosity, the ratio between inverse Compton and synchrotron luminosities and a decrease in the peak frequencies. This reflects the progressive trend from FSRQ, to High and Low Energy Peaked BL Lacs (HBL and LBL, respectively; Padovani & Giommi 1995). Furthermore, the extended luminosity of HBL and LBL differs, on average, by a factor $\sim 100$, probably due to the (although weak) correlation between the nuclear and extended radio emission (e.g. Giovannini et al. 1988).

In order to determine if/how Centaurus A fits in this blazar sequence we “beamed” its SED with a typical BL Lac Doppler factor, $\delta_{\text{BL}} \sim 15$, starting from our fiducial value $\delta \sim 1$. Clearly the effect of this procedure is to shift the observed SED by a factor of $\delta_{\text{BL}}$ in frequency and $\delta_{\text{BL}}^2$ in luminosity ($a = 3$ and $a = 4$ in the case of emission from a continuous jet or an emitting sphere, respectively). The resulting peak frequencies are $\log \nu_{\text{c}} \sim 14$ and $\log \nu_{\text{v}} \sim 20.5$ and their luminosities are in the range $\log \nu L_{\nu} = 45 - 46$ and $\log \nu L_{\nu} = 45.5 - 46.5$, for the synchrotron and inverse Compton components respectively. Although this procedure has large uncertainties, the inferred values are typical of LBL. This also appears to be consistent with the fact that the extended radio power of Centaurus A ($L_{408\text{MHz}} \sim 10^{31.5}$ erg s$^{-1}$) is also in the range spanned by LBL, although close to its lower end. Therefore, although velocity structures appear to be present in the jet, it is plausible that the physical conditions in the external layer might be similar to those of the spine. Clearly, it is very important to further investigate this issue by considering a large sample of objects.

5 CONCLUSIONS

For the first time we have built the overall nuclear SED of Centaurus A, the only radio galaxy for which data provide a good coverage of the nuclear emission from the radio to the $\gamma$-ray band. The SED appears to be remarkably similar to that of blazars, as in a $\nu - \nu L_{\nu}$ representation it is well represented by two broad peaks located in the far-infrared band and at $\sim 0.1$ MeV. Although we cannot exclude that the emission observed at the various wavelengths might be produced by different components/radiation processes, we have shown that a simple one zone, homogeneous SSC model is adequate to account for the overall spectral distribution. Note that in this framework, the high IR polarization of the Centaurus A nucleus (Bailey et al. 1986, Capetti et al. 2000) is readily explained as due to synchrotron emission.

In this SSC scenario we have found that the physical parameters (magnetic field, particles energy distribution etc.) are in the range usually found for BL Lacs, with the noticeable exception of a beaming factor lower than the values usually derived from fitting the SED of BL Lacs ($\delta \sim 15 - 20$). This is qualitatively expected when a relativistic jet is seen at large angles of sight.

However, while these results provide evidence that Centaurus A is indeed a misoriented BL Lac and support the
unification scheme for low luminosity radio-loud AGNs, a more quantitative analysis shows that the beaming factor derived for it, δ ∼ 1, is not simply compatible with being originated in a misoriented fast (Γ ∼ 15 – 20) blazar component. In fact, for the viewing angle derived from VLBI observations (∼ 50° – 80°), much smaller values of δ would be expected. This suggests that the emission from jets can be represented by a fast (highly relativistic) spine and a slower layer, supporting the indications we have found through the comparison of complete samples of BL Lacs and radio galaxies (Chiaberge et al. 2000) and in agreement with other independent observational evidence (e.g. Laing 1993, Laing et al. 1998, Giovannini et al. 1999, Swain et al. 1998). The jet spine dominates the emission in blazars and due to the large Lorentz factors, its emission falls very rapidly as the angle of sight increases. Instead the slower layer would dominate in radio galaxies. For a range of viewing angles (which depends on the details of the jet velocity structure), the spine and layer emission can provide a similar level of emission and thus be observed simultaneously. If these two components have significantly different spectral properties (although this is not suggested by our analysis), the resulting SED of these intermediate objects might be rather complex, e.g. with multiple emission peaks.

Recent results suggest that the whole population of blazars follows a sequence that links the overall spectral properties (in particular the luminosity and location of the emission peaks) with the nuclear radio luminosity, in turn related to the extended one. Centaurus A nicely fits into this trend as by “beaming” its SED for a typical BL Lac Doppler factor the frequency and the amplitude of the peaks, as well as the (unbeamed) extended radio power, are typical of LBL.

Clearly the presence of significant emission from a layer has important consequences also on the statistics of the sources, in particular for the comparison of the counts and luminosity functions of the beamed and parent populations. In these estimates, the role of the layer emission can be identified with that played by some ‘isotropic’ emission, quantified by the relative fraction f of beamed and un–beamed luminosities (Urry & Shafer 1994). The results found for Centaurus A would correspond to f ∼ 1. This is in contrast with the much smaller values inferred by the modeling, as required by both the relative small number of beamed sources (implying high Γ) and the limits on the total luminosity range spanned by the whole beamed and unbeamed populations.

The presence of a high energy peak in Centaurus A at ∼ 0.1 MeV raises the question of the contribution of radio galaxies to the gamma–ray background radiation as already suggested by Steinle et al. (1998). However, if all radio galaxies emit the same fraction of bolometric luminosity as Centaurus A in this band, despite their much larger number density, their contribution would be of only ∼ 10 per cent relative to that produced by blazars, because of the much higher power radiated by beamed sources of similar extended radio emission.

Simultaneous multiwavelength observations of a large sample of radio galaxies, taking advantage of the future generation of γ–ray instruments, will allow us both to confirm our present findings and to establish if the trends observed in blazars occur also in their parent population. This would provide strong support to the unification models and important information on the physical structure of relativistic jets.

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