Astron. Astrophys. 331, L57–L60 (1998)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Non-thermal pair model for the radio-galaxy Centaurus A

A.Marcowith[1,2], G. Henri[2], and N. Renaud[2]

[1] Max-Planck-Institut für Kernphysik, Postfach 10 39 80, D-69029 Heidelberg, Germany,
[2] Laboratoire d'Astrophysique de l'Observatoire de Grenoble, Université J. Fourier, BP 53, F-38041 Grenoble Cedex 9, France

Received 16 September 1997 / Accepted 30 October 1997

Abstract. In this letter we consider the production of hard X-ray spectrum of the radio galaxy Centaurus A by a relativistic electron-positron beam scattering soft photons coming from an accretion disk. The spectral break of order of 0.7 observed at ~ 120 keV in the 1991 high emission state is explained by $\gamma-\gamma$ absorption of soft gamma-ray photons. The misaligned nature of the relativistic jet explains a redshifted spectral break with regard to pair creation energy threshold. We fit the data with a jet direction making an angle of $80°$ with the line of sight. We also consider lower Thomson optical depth solutions, and we apply them to the 1992-1994 low state of activity of the source.

Key words: galaxies: active – galaxies: individual Cen A – radiation mechanisms: nonthermal – Gamma-rays: theory

1. Introduction

The radio galaxy Centaurus A (NGC 5128-PKS 1322-427) has been recently observed at hard X-rays with the *Oriented Scintillation Spectrometer Experiment* (OSSE) instrument on the *Compton Gamma Ray Observatory* (CGRO, Johnson et al. 1993). Although intrinsically weaker than other Quasars, these observations have confirmed Centaurus A to be one of the brightest active galactic nuclei at 100 keV. But other peculiar spectral features have been found combining OSSE and COMPTEL observations (Kinzer et al. 1995; Steinle et al. 1996, 1998). (1) The existence of two states of activity: (i) a high one, observed in 1991 during the VP 12 phase of simultaneous OSSE-COMPTEL-EGRET observations, with a hard X-ray spectrum indicating spectral softening above ~ 120 keV with the possibility of a broken power-law with a spectral break of 0.7 ± 0.15, (ii) a low state observed by OSSE for all periods except the VP 12 one. (2) A spectral break moving to higher energies (~ 150 keV) for lower emission states. (3) An energy spectral index of $\sim 0.7 \pm 0.08$ below the break independent of the intensity. (4) A peak of energy at ~ 200 keV with a luminosity in the 50 keV-1 MeV band of $\sim 7.10^{42}$ erg/s. (5) Finally long and short term time variability ranging from months to less than one day.

Send offprint requests to: G. Henri

To reproduce these observations, Skibo et al. (1994) have considered the effect of cold (with $kT_{\rm e} \ll m_{\rm e}c^2$) electron clouds on beamed radiation produced in the nuclei. The electrons can move with bulk relativistic speeds along the jet axis and Compton scatter the incident power-law radiation. The beam can either be mono-directional (emitted by a point source), or isotropic in a particular relativistic frame. The beamed photons are thought to be produced by Inverse Compton emission involving low energy photons coming from the jet itself (synchrotron radiation) or from the disk. In each cases, the produced photons are energetic, and usually the Compton scattering on cold electron clouds takes place in the Klein-Nishina regime. The resulting spectrum shows an exponential cut-off above 500 keV, but can fit well the OSSE data with a power-law in the $50 - 500$ keV range. However, the simultaneous COMPTEL (Steinle et al. 1996, 1998) and non-simultaneous EGRET (Thompson et al. 1995) detections make improbable the exponential shape of thermal Comptonisation models, and tend to favor non-thermal spectra with a break and beaming models.

The radio to X-ray emission from the jet is believed to be associated with synchrotron and/or Inverse Compton emission (Morganti et al. 1991; Hawarden et al. 1993). However, the misaligned nature of the jet is supported by the discovering of subluminal motions by VLBI technics (Meier et al. 1991), counter-jet detections (Jones et al. 1996), and IR polarimetry studies (Bailey 1986). In such case, the Doppler factor of the relativistic jet is lower than 1, and the usual break observed in radio-loud objects, such as 3C273, above 1 MeV should be redshifted around 100 keV, which is close to the observed value.

However, most of these models (Dermer & Schlikeiser 1993; Sikora et al. 1994) predict a spectral break of 0.5, due to Incomplete Compton or synchrotron cooling, in contradiction with the 1991 OSSE-COMPTEL and EGRET data. In a previous paper (Marcowith, Henri, Pelletier 1995, thereafter MHP) we have thus considered the role played by an electron-positron pair plasma in modeling the X-ray and gamma-ray spectra of Radio Loud Quasar. In our scheme, the relativistic particles are embedded and confined in a subrelativistic MHD (magneto-hydrodynamical) jet launched from the disk by magnetic effects (see MHP). This double structure, introduced first by Sol, Pelletier and Asséo (1989) to explain the radio structure of extragalactic sources, is known as the "two-flow" model. In this model, high energy photons are produced by Inverse Compton effect resulting from the interaction between soft photons coming from an accretion disk and a relativistic pair plasma, which is itself created in-situ by $\gamma - \gamma$ interactions. This can lead to the appearance of an energy dependent gamma-ray photosphere, producing an MeV spectral break. The energy spectral index above the break is approximately twice as large as the spectral index below (MHP). For the high state of Cen A emission, as mentioned in points (i) and (iii) above, this relation is indeed verified. We thus argue that the hard X-ray spectrum of Centaurus A is produced by such a mechanism. The X-ray compactness at 100 keV derived from variability observations (Jourdain et al. 1993; Kinzer et al. 1995) is $\sim 0.01 - 0.1$ but can reach values around 1 if the emission is anisotropic with a Doppler factor lower than 1 as it must be here, which supports the presence of pairs.

The letter is organized as follows: the section 2 recalls the main physical developments and results of the MHP paper, the section 3 refers to the comparison of the model with the observations. We conclude in Sect. 4.

2. The high energy model for extragalactic sources

2.1. The "two-flow" model

The paradigm of the present work is the two flow model as proposed by Sol et al. (1989) to explain radio phenomena in active galactic nuclei. The jet structure is divided in two parts. The first component is a subrelativistic MHD ($v_j \sim 0.3c$) electron-proton jet carrying most of the kinetic energy, flowing out of the central regions of the nuclei, launched from a magnetized accretion disk (Ferreira & Pelletier 1995). This flow is responsible for large scale structures such as two-sided kpc-Mpc jets, extended lobes, and hot spots where the kinetic energy can be dissipated by a strong shock (Pelletier & Roland 1986). The second component is a relativistic electron-positron pair beam confined by the jet and responsible for the small scale structures (≤ 100 pc) such as superluminal motions observed in VLBI.

This model was applied to high energy extragalactic sources (Henri & Pelletier 1991; Henri et al. 1993, and MHP). All these works deal with a relativistic pair plasma to produce high energy photons (γ and X-ray) by Inverse Compton scattering (IC) of soft photon emitted by an accretion disk. The anisotropy of the incoming photons have different consequencies. First, the incident radiation power is converted into bulk motion by the anisotropic Compton emission of the pair plasma. This is the so called "Compton rocket" effect (O'Dell 1981). Without reheating, this effect is not efficient enough to explain the superluminal motions observed in VLBI (Phinney 1982). But, as the sub-relativistic jet can carry a large amount of energy without suffering strong IC losses, it can act as an energy reservoir for the beam. The pairs can be re-accelerated continuously, the rocket effect is extended on longer distances and final bulk Lorentz factors of order of 10 can be achieved (Henri & Pelletier 1991; Renaud & Henri 1998). Secondly, the X- and gamma-ray photons are beamed by Doppler boosting effect in the jet direction, and can explain the huge high energy emission by lowering the compactness of the high energy source. In this case, a gamma-ray photosphere may exist in the beam structure (MHP, under different hypothesis see also Blandford & Levinson 1995). The high energy spectrum is characterized by a spectral break associated to the lack of gamma-ray (or hard X-ray in the present case) photons absorbed in the pair production process. The non-thermal X-ray spectrum is produced internally by IC effect.

2.2. The high energy spectrum

In the present model, the high energy photons are produced by IC effect on soft photons. The seeds photons can be internally produced as synchrotron radiation (Ghisellini 1991; Marscher & Bloom 1996), or come externally from a disk emission. In this last case, they can be scattered by surrounding clouds (Sikora et al. 1994), or come directly like in Dermer & Schlickeiser (1993). As in MHP, we will only consider here the photons coming from a standard accretion disk (Shakura & Sunyaev 1973). The high energy spectrum is thus a pure Inverse Compton spectrum altered by the pair creation. We recall here the main results of MHP's model.

2.3. The pair model scenario

Thereafter, the photons energies are in $m_e c^2$ units, the subscripts s and 1 are used respectively for the soft disk photons and for the high energy scattered photons. The pair density distribution is assumed to be a power-law with an index $1 \leq s \leq 3$, taken between $\gamma_{min} = 1$ and γ_{max}. It is supposed to be isotropic in a frame moving with a relativistic speed $\beta_b c$. A small number of relativistic particles is supposed to be created near the black hole at the base of the jet by different effects such as Penrose process, or magnetic reconnection. Then, some soft photons (with a density $n_s \sim 10^{12}\mathrm{cm}^{-3}(M/10^8 M_\odot)$) are IC scattered to produce X and gamma-ray photons. In the moving frame the opacity to pair production varies as

$$\tau_{\gamma\gamma}(z, \varepsilon'_1) \simeq \sigma_T^2 r(z)^2 n'_s(z) n'_e(z) (\varepsilon'_s(z)\varepsilon'_1)^{(s-1)/2} , \quad (1)$$

where $n'_e(z)$ is the pair density at a distance z above the black hole.

The huge number of soft photons leads to creation of new pairs along the jet. As the pair cascade becomes saturated, the particle population increases by pair production. When it becomes optically thick, the soft photon population decreases by IC absorption. Then pair production ceases and the pair density decreases, being governed by annihilation that takes place on a longer timescale. The evolution of the particle and photon populations is described by two continuity equations (see MHP, Eq. (57)). The boundary conditions were chosen in MHP at a distance z_0 where the soft photons are strongly (exponentially) absorbed by the pairs over a length as short as the width of the jet ($r(z_0) = 10 r_G$). The plasma becomes there optically thick for both pair production and Thomson scattering, namely

$$\tau_{\gamma\gamma} = \tau_0 \leq 1$$

$$\tau_T \ = \ \sigma_T n'_{e0} r(z_0) = 1 \ , \tag{2}$$

z_0 then denotes approximately the localization of the 0.511 MeV photosphere. The opacity parameter $\tau_0 \leq 1$ prevents the solutions from an unphysical strong absorption. z_0 is to be found by integrating the system backwards, down to small z, where the soft photon density matches n_{sD} emitted by the disk. For $z \geq z_0$ the high energy photons $\varepsilon_1 \geq 1$ are still absorbed by the pair production effect (see Eq. (1)). Only the absorption of $n_s(z)$ by IC effect and $n_e(z)$ by annihilation can explain the drop of $\tau_{\gamma\gamma}$, and the formation of an energy dependant gamma-ray photosphere. This differential absorption explains the spectral break observed above MeV energies in the laboratory frame.

3. Comparisons to the Centaurus A X-ray spectrum

3.1. The parameters of the model

The free parameters used in this model are:

- The angle between the observer and the jet axis, θ_1.
- The mass of the central object M (in solar masses $M_\odot$), which mainly controls the radius of the jet, taken to be $10 r_G$.
- The accretion rate $\dot{M}$ (in $M_\odot/yr$).
- The particle distribution index s, related to the X-ray energy spectral index $\alpha_< = (s-1)/2$.
- The opacity parameter τ_0.

In fact, the high energy spectrum is not very sensitive to variations of the accretion rate and hence to the disk luminosity (see MHP for explanations). The spectral index is constrained by the the observations below the spectral break, and the parameter τ_0 is found to take limited values around 0.1. This leads to only two real free parameters; the angle θ_1 and the radius of the jet (or equivalently the central mass with the above assumption). It is important to realize that other important parameters, as the particle density, the distance from the center, the plasma velocity, are *not* free but are linked to the above quantities through the differential equations and their boundary conditions.

We apply our model to the 1991 simultaneous OSSE/-COMPTEL (VP 12) observations, together with EGRET results from Thompson et al. (1995). The best fit for a cylindrical jet is given in Fig. 1.

For a Schwarzschild black hole we used the following set of parameters: $M = 3.10^6 M_\odot$, $\dot{M} = \dot{M}_{Edd}$, $s = 2.7$, $\tau_0 = 0.08$, $\theta_1 \sim 80°$, where $\dot{M}_{Edd}$ denotes the Eddington accretion rate. The internal radius of the disk is $r_i = 3r_G$ and the external one is $r_e = 3000 r_G$. The emission zone z_0 is found to be located around 100 r_G.

The derived angle confirms the misaligned nature of the Centaurus A jet and is in agreement with the previous derivations of the direction of the line of sight inferred from HII distributions studies (Graham (1979)), which is a little smaller.

3.2. A red-shifted spectral break

For the high state, the spectral break verifies well the relation $\alpha_> - \alpha_< = \alpha_< = (s-1)/2 \sim 0.7$. Such a value is explained

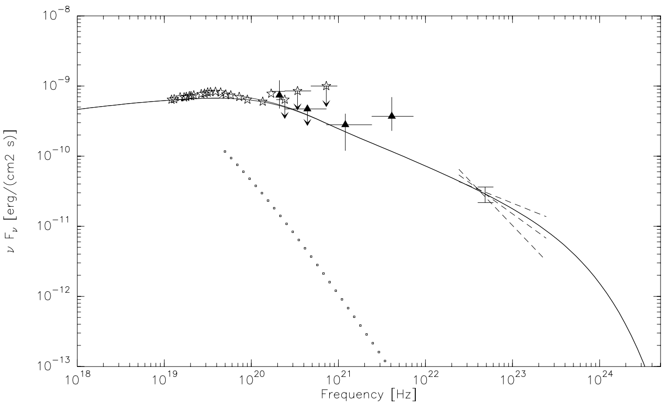

Fig. 1. Comparison between the high state of emission in 1991 and our model (solid line). The dotted line represents the annihilation component. The parameters are defined in the text. OSSE data are from Kinzer et al. (1995), COMPTEL data from Steinle et al. (1996) and EGRET data from Thompson et al. (1995) (dashed lines).

by the strong (exponential) absorption of the soft photons in the Thomson optically thick plasma at z_0 where the pair density reaches values of order of $10^{11}\mathrm{cm}^{-3}$ for Centaurus A.
As pointed before, this strong absorption zone also corresponds to the gamma-ray photosphere of 0.511 MeV in the pair plasma rest frame. In the observer frame a Lorentz transformation shifts the energy of this optically thin region to $0.511 D_0$ MeV, where $D_0 = [\gamma_{b0}(1-\beta_{b0}\cos\theta_1)]^{-1}$ is the Doppler factor at the emission zone.

If the soft photon source is a standard accretion disk the bulk Lorentz factor of the beam, for $r_i < z < r_e$, scales as (see Eq. (36) in MHP)

$$\gamma_b \equiv (z/r_i)^{1/4}, \tag{3}$$

In the present case, the infered angles between the jet and the line of sight directions give $\cos\theta_1 \ll 1$, the Doppler factor at the emission zone $D_0 \sim \gamma_{b0}^{-1}$ is lower than 1, and the spectral break is red-shifted for an external observer. For a spectral break at $\sim 120 - 150$ keV depending of the state of the object we obtain $\gamma_{b0} \sim 4.3 - 3.4$. This corresponds well to the value expected around 100 r_G The annihilation line, which plays a minor role here, is also red-shifted down to an energy of $0.511 D_0$ MeV (see Eq. (67) in MHP).

3.3. Low states of activity

The 1992-1994 low state of activity shows a spectral softening located at a higher energy ($\sim$ 150 keV). Below the break, the energy spectral index (~ 0.7) does not seem to depend on the intensity level. Only the higher energy data from OSSE, COMPTEL and EGRET can constrain value of the spectral break. Unfortunatly the OSSE-EGRET (VP 316) and COMPTEL (1992-1993) observations are not simultaneous, and precise value of the break can not be deduced. We argue that in our scheme the low state of activity can be associated with a less efficient pair formation process. This effect can be quantified by relaxing the "type I" opacity conditions used in our simulations (see Eq. (2)).

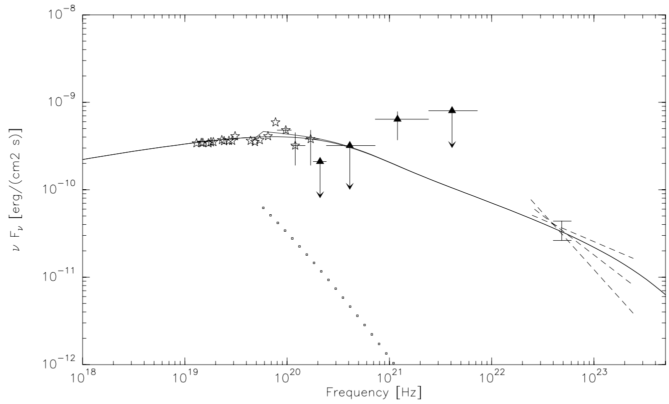

Fig. 2. Comparison between the 1992-1994 low state of emission and the model. The parameters are defined in the text. EGRET data are derived from Thompson et al. (1995) summing all phase 2 observations (P2).

The pair plasma is taken now to have a *longitudinal* (instead of *transverse*) Thomson optical depth of 1 at a distance z_1 where the corresponding opacity to pair production is τ_1. The "type II" opacity conditions now read:

$$\tau_{\gamma\gamma} = \tau_1$$
$$\tau_T = \sigma_T n_{e0} z_1 = 1 \,, \quad (4)$$

There is no simple relation between the two systems $[\tau_0, z_0]$ and $[\tau_1, z_1]$ due to the non-linear factor containing $\tau_{\gamma\gamma}$ (see Eq. (52) in MHP) in the continuity equations. In particular, low density solutions cannot be described by type I conditions. The soft photon and the particle densities with type II conditions are derived in the same way as for the type I.

The best fit of the low state is given in Fig. 2, with the parameters $M = 10^6 M_\odot$, $\dot{M} = \dot{M}_{Edd}$, $s = 2.6$, $\tau_1 = 0.15$, $\theta_1 \sim 80°$. The model predicts $z_1 = 70 r_G$.

4. Conclusion

In the present work, the high and low states of the radio galaxy Centaurus A are investigated in the framework of the two flow model. High energy radiations are produced by a relativistic non-thermal pair plasma scattering soft photons coming from a standard accretion disk. Opacity to pair production can explain the spectra softening observed between $120 - 150$ keV. The theoritical spectral break $\Delta\alpha = \alpha_< = 0.7$ matches the 1991 high state data. Due to large viewing angles, the beamed radiations are redshifted with regard to the pair production threshold energy 0.511 MeV, giving typical Doppler factors of order of 0.3. The low state of activity observed between 1992 and 1994 can be associated with a less efficient pair plasma creation process, and can be fitted if the pair plasma has a longitudinal Thomson optical depth of one.

Acknowledgements. We would like to thank Dr H. Steinle for fruitful discussions about COMPTEL and EGRET results.

References

Bailey J., Sparks W.B., Hough J.H., et al., 1986, Nature 322, 150
Blandford R.D., Levinson A., 1995, ApJ 441, 79
Dermer C.D., Schlickeiser R., 1993, ApJ 416, 458
Ferreira J., Pelletier G., 1995, A&A 295,807
Fichtel C.E., Bertsch D.L., Chiang J., et al., 1994, ApJS 94, 551
Ghisellini G., 1991, MNRAS 248, 14
Graham J. A., 1979, ApJ 232, 60
Hawarden T.G., Sandell G., Matthews H.E., et al., 1993, MNRAS 260, 844
Henri G., Pelletier G., 1991, ApJ 383, L7
Henri G., Pelletier G., Roland J., 1993, ApJ 404, L41
Johnson W.N., Kinzer R.L., Kurfess J.D., et al., 1993, ApJS 86, 693
Jones D.L., Tingay S.J., Murphy D.W., et al., 1996, ApJ 466, L63
Jourdain, E., Bassani L., Roques J.P., et al., 1993, ApJ 414, 586
Kinzer R.L., Johnson W.N., Dermer C.D., et al., 1995, ApJ 449, 105
Marcowith A., Henri G., Pelletier G., 1995, MNRAS 277, 681 (MHP)
Meier D.L., et al., 1993, In: Davis R.J., Booth R.S. (eds.) Sub-Arcsecond Radio Astronomy,Cambridge University Press, p 201
Morganti R., Robinson A., Fosbury R.A.E., et al., 1991, MNRAS 249, 91
Morini M., Anselmo F., Molteni D., 1989, ApJ 347, 750
O'Dell S.L., 1981, ApJ 243, L147
Pelletier G., Roland J., 1986, A&A 163, 9
Phinney E.S., 1982, MNRAS 198, 1109
Renaud N., Henri G., 1998, MNRAS, submitted
Sikora M., Begelman M.C., Rees M.J., 1994, ApJ 421, 153
Skibo J.G., Dermer C.D., Kinzer R.L., 1994, ApJ 426, L23
Sol H., Pelletier, G., Asséo, E., 1989, MNRAS 237, 411
Steinle, H., et al., 1996, In: Kirk J.G., Camenzind M., von Montigny C., Wagner S. (eds) Proc. of Gamma-ray Emitting AGN, Heidelberg, p 15.
Steinle, H., Bennett, K., Bloemen, H., et al., 1998, A&A 330,97

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.