Spectral modelling of 1 ES 1218+30.4

M. Rüger, F. Spanier and K. Mannheim
Lehrstuhl für Astronomie, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany

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ABSTRACT
We employ a time-dependent synchrotron-self-Compton code for modelling contemporaneous multiwavelength data of the blazar 1 ES 1218+30.4. The input parameters of the model are used to infer physical parameters of the emitting region. An acceptable fit to the data is obtained by taking into account a stellar emission component in the optical regime due to the host galaxy. The physical parameters inferred from the fit are in line with particle acceleration due to the Fermi mechanism providing $s = 2.1$ spectra. From the properties of the host galaxy in the optical, we estimate the central black hole mass and thus confirm that the jet power injected into the emission region is in the sub-Eddington regime, as expected for BL Lacertae objects.

Key words: radiation mechanisms: non-thermal – BL Lacertae objects: individual: 1 ES 1218+30.4 – gamma-rays: theory.

1 INTRODUCTION
Among the class of active galactic nuclei (AGN), blazars are special in showing a spectral energy distribution (SED) that is strongly dominated by non-thermal emission across a wide range of wavelengths, from radio waves to gamma-rays, and rapid, large-amplitude variability. Presumably, these characteristics are due to a relativistic jet emitted at a small angle to the line of sight, emitting Doppler-boosted synchrotron and inverse Compton radiation and thus washing out to a variable extent the emission from the accretion flow and host galaxy.

The synchrotron and inverse Compton emission could result from primary accelerated electrons, from accelerated protons or from secondary electrons arising in electromagnetic cascades initiated by pion and pair production (e.g. Mannheim 1993).

The high-peaked BL Lacs (HBLs) show a peak in their SED in the X-ray regime, suggesting that an inverse Compton peak should occur at correspondingly high gamma-ray energies. In fact, a large fraction of the known nearby HBLs have already been discovered with Cherenkov telescopes, such as HESS, MAGIC and VERITAS.

In those cases where the blazars have been detected at gamma-ray energies, the SED shows two bumps, one at infrared-to-X-ray energies and the other at gamma-ray energies. So far, the reasons for the variation of the peak energies are unknown, and their relation with fundamental parameters of the central engine, the black hole mass, spin and accretion rate is far from settled.

Models of the radiation processes behind the blazar emission are a key issue to improve our understanding of blazars. The diagnosis of the observed spectra using radiation models allows to infer the physical conditions prevailing in them and to discern their relation with fundamental parameters. However, without a prescription of the relativistic particle spectra, the models effectively map radiation on to particle spectra, and the error in the inferred physical conditions is correspondingly large. On the other hand, using theoretically favoured particle spectra most strongly constrains the physical conditions prevailing in the sources, and this may eventually lead to a consistent physical explanation.

The HBL 1 ES 1218+30.4 has been discovered as a candidate BL Lac object on the basis of its X-ray emission and has been identified with the X-ray source 2A 1219+30.5 (Wilson et al. 1979; Ledden et al. 1981). For the first time, 1 ES 1218+30.4 has been observed at very high energies (VHE) using the MAGIC telescope in 2005 January (Albert et al. 2006). Simultaneous optical data has been provided by the KVA telescope on La Palma. Latest TeV data have been provided by the VERITAS telescope (VERITAS Collaboration: Acciari et al. 2009).

Here, we present the kinetic equation and numerical code describing the synchrotron-self-Compton (SSC) emission (Section 2). The particular emphasis lies on an accurate treatment of the Klein–Nishina turnover which is important at very high gamma-ray energies. Previous works (cf. Böttcher & Chiang 2002 and references therein) provided good results in the scope of HBL modelling. Our approach is quite similar to these models except for details in the treatment of the particular processes. External Compton effects are left out in order to use a minimum number of parameters, which are sufficient for dealing with HBLs. In Section 3, we apply our code to 1 ES 1218+30.4 referring in particular to the MAGIC and VERITAS data and give a set of physical parameters for the most acceptable fit. Finally, we discuss our results in the light of particle acceleration theory.

2 THE MODEL
To model the observational data, we use the well-established SSC model (e.g. Maraschi, Ghisellini & Celotti 1992). We assume a...
spherical, homogeneous emission region – coined blob – containing isotropically distributed non-thermal electrons and a randomly oriented magnetic field.

Due to the presence of this magnetic field the electrons emit synchrotron radiation. The photons are then scattered off the same electron population via the inverse Compton process. The resulting spectrum shows the typical two-bump structure commonly found in blazars.

In the following section, the governing equations of the SSC model are explained.

2.1 Photon distribution

To determine the time-dependent SED of blazars, we solve the differential equation for the differential photon number density, obtained from the radiative transfer equation, including the corresponding terms with respect to SSC model

$$\frac{\partial n_{ph}(\nu)}{\partial t} = R_S(\nu) - R_{SSA}(\nu) + R_C(\nu) - \frac{n_{ph}(\nu)}{T_{esc}}. \quad (1)$$

2.1.1 Synchrotron radiation

In the following context, the well-known $\delta$ approximation (Felten & Morrison 1966; Schlickeiser 2002) is applied to describe the synchrotron radiation in a convenient way. Thus, the synchrotron photon production rate $R_S$ is given by

$$R_S(\nu) = \frac{8mcn_e(\gamma_e)cP_5(\gamma)}{3eB^3v\gamma_e}, \quad (2)$$

with the pitch-angle-averaged total power $P_5$ emitted by a single electron having Lorentz factor $\gamma$ (Ginzburg & Syrovatskii 1969; Blumenthal & Gould 1970; Rybicki & Lightman 1979)

$$P_5(\gamma) = \frac{4e^4B^2(\gamma^2 - 1)}{9m_e^2c^3} \quad (3)$$

and $\gamma_e$ being a function of $v$,

$$\gamma_e(v) = \sqrt{\frac{16mcv}{3eB}}, \quad (4)$$

obtained from the pitch-angle-averaged critical synchrotron frequency.

2.1.2 Synchrotron-self-absorption

In optically thick regimes, the emitted synchrotron radiation is absorbed by the emitting electrons itself. This is described by the synchrotron-self-absorption coefficient,

$$\epsilon_v = -\frac{1}{12} \frac{c}{\nu^2eB^3} n_e(\gamma_e) \frac{\partial}{\partial \nu} \left[ \frac{n_e(\gamma)}{\gamma^2} \right] \nu_e, \quad (5)$$

which leads to the absorption rate

$$R_{SSA}(\nu) = c\epsilon_v n_{ph}(\nu). \quad (6)$$

2.1.3 Compton scattering

The second main feature of the SSC model is Compton scattering of the synchrotron photons by the emitting electrons themselves.

Here, the full Klein–Nishina cross-section is used to calculate the photon production rate

$$R_C(\nu) = \int d\gamma n_\gamma(\gamma) \times \int d\epsilon_1 \left[ n_{ph}(\epsilon_1) \frac{dN(\gamma, \epsilon)}{d\nu d\epsilon} - n_{ph}(\epsilon) \frac{dN(\gamma, \epsilon)}{d\nu d\epsilon} \right]. \quad (7)$$

The formula was taken from Pe’er & Waxman (2005) with minor corrections according to Coppi & Blandford (1990). The photon energies are rewritten in terms of the electron rest mass, so that $h\nu = \epsilon mc^2$ for the scattered photons and $h\nu = \epsilon mc^2$ for the target photons. To make use of the full Klein–Nishina cross-section, we applied the approximate inverse Compton spectrum (Jones 1968) of a single electron scattered off by a unit density photon field

$$\frac{dN(\gamma, \epsilon)}{d\nu d\epsilon} \approx \frac{2\pi\gamma^3}{\epsilon_1} \left[ q^\prime\ln q + (1 + 2q'_1)(1 - q') \right] + \frac{1}{2} \frac{(4\epsilon_1\gamma q')^2}{(1 + 4\epsilon_1\gamma q')^2} \left( 1 - q'' \right), \quad (8)$$

where $q'' = \epsilon/[4\epsilon_1\gamma^2(1 - \epsilon/\gamma)]$ and $1/(4\epsilon_1^2) < q'' < 1$. This equation is valid for $\epsilon_1 < \epsilon \leq 4\epsilon_1\gamma^2/(1 + \epsilon_1\gamma)$. The corresponding ordinary Compton spectrum is approximately given by

$$\frac{dN(\gamma, \epsilon_1)}{d\nu d\epsilon_1} \approx \frac{2\pi\gamma^3}{\epsilon_1^2} \left[ q'_1 - 1 \right] \left( 1 + \frac{2}{q'_1} \right) - 2 \ln q'_1, \quad (9)$$

with $q' = 4\gamma^2\epsilon/\epsilon_1$ and target photon energies in the range $\epsilon_1/4\gamma^2 < \epsilon < \epsilon_1$.

2.1.4 Photon escape

The last term describing the evolution of the photon number density represents the photons escape rate. Here the photon escape time $T_{esc}$ is given by the light crossing time

$$T_{esc} \approx \frac{R_0}{c}, \quad (10)$$

where $R_0$ is the radius of the emitting blob. The escape time is chosen to be the light crossing time of the photons.

2.2 Electron distribution

The time evolution of the electron distribution is described by the kinetic equation

$$\frac{\partial n_e(\gamma)}{\partial t} = \frac{\partial}{\partial \gamma} \left[ n_e(\gamma) \left( \gamma_\gamma + \gamma_C \right) \right] - \frac{n_e(\gamma)}{T_{esc,e}} + Q_{em}(\gamma). \quad (11)$$

The synchrotron loss is given by $\gamma_C = P_5(\gamma)/mc^2$ with the synchrotron power $P_5(\gamma)$ (cf. 3). $T_{esc,e} = \eta R_0/c$ describes the electrons escaping from the emission region, where $\eta$ is an empirical factor. The inverse Compton losses $\gamma_C$ including the full Klein–Nishina cross-section are adopted following Schlickeiser (2002)

$$\gamma_C = \frac{3\sigma_T c}{4} \int_0^\infty d\epsilon_1 \epsilon_1 n_{ph}(\epsilon_1) \times \int_0^1 dq \frac{\Gamma_e^2}{(1 + \Gamma_e q)^3} G(q, \Gamma_e) \quad (12)$$

with

$$G(q, \Gamma_e) = \left[ 2q \ln q + (1 + 2q)(1 - q) + \frac{(\Gamma_e q)^2(1 - q)}{2(1 + \Gamma_e q)} \right]. \quad (13)$$

$$\Gamma_e = 4\epsilon_1\gamma/(mc^2), \quad q = \epsilon/[(\gamma_e\gamma mc^2 - \epsilon)]. \quad (14)$$

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As an injection function $Q_{\text{inj}}$, we use a power law combined with an exponential cut-off:

$$Q_{\text{inj}}(\gamma) = K \gamma^{-s} \exp\left(\frac{-\gamma}{\gamma_{\text{max}}}\right),$$

with the Lorentz factor $\gamma$, the normalization constant $K$, cut-off energy $\gamma_{\text{max}}$ and the spectral index $s$. Using an injection function constant in time one yields an equilibrium solution for $n_e(\gamma)$ being constant in time.

### 2.3 Numerics

To obtain a model SED using the SSC formalism, we solve the coupled equations (1) and (11) numerically in our code framework. With respect to stability issues, we use the Crank–Nicholson scheme (Press 2002) to compute the synchrotron part of the right-hand side of both electron equation and photon equation. The code was tested carefully and stands the challenge of computing the equations in a range of 20 orders of magnitude. All single effects (synchrotron radiation/losses, Compton scattering/losses) have been cross checked with analytical solution and approximation as well as with numerical integration crosschecks using Mathematica. Also, a comparison with existing codes was done successfully (as long as the models themselves were comparable).

### 3 Results

In Fig. 1, we show the results of the application of the code to the data of the HBL 1 ES 1218+30.4. Here, we present an SSC-model curve which fits the data in the X-ray and VHE regimes. The corresponding parameters are listed in Table 1. With these values, we end up in an equilibrium state with a cooling break energy of the electron distribution $\gamma_{\text{break}} = 6 \times 10^4$.

The VHE data shown here have been discovered by the MAGIC telescope (Albert et al. 2006). Lately, the VERITAS telescope could confirm this detection. As shown in VERITAS Collaboration: Acciari et al. (2009), the measured flux matches each other in the overlapping energy regime.

The data in the X-ray regime have been taken by Swift between 2005 March and December (Tramacere et al. 2007). Another set of X-ray data was obtained by the BeppoSAX experiment in 1999 (Donato, Sambruna & Gliozzi 2005). It is remarkable that in spite of a lag of 6 years between these observations there is no difference in the X-ray flux. Together with the constant TeV flux level this is a strong argument for an almost constant background of non-thermal electrons in a constant magnetic field.

The KVA data point shown in Fig. 1 was obtained simultaneously to the MAGIC observation of 1 ES 1218+30.4. One can also see that the SSC model is not able to fit this data point. This discrepancy can be resolved by taking the NASA/IPAC Extragalactic Database (NED) and Two-Micron All-Sky Survey (2MASS) data (Chen, Fu & Gao 2005) surrounding the optical KVA point into account. This set of data points has been modelled by a simple blackbody spectral distribution with a temperature $T = 4500$ K and a radius.

![Figure 1. Overall SED of 1 ES 1218+30.4. Green crosses show the MAGIC data (Albert et al. 2006), grey triangles the VERITAS data (VERITAS Collaboration: Acciari et al. 2009). The TeV data have been de-absorbed by applying the extragalactic background light (EBL) correction model of Kneiske et al. (2004). The filled cyan box represents the simultaneously obtained KVA data point. In the X-ray range, Swift (Tramacere et al. 2007) and BeppoSAX (Donato et al. 2005) data are plotted as blue stars and red crosses. The 2MASS data (red open triangles; Chen et al. 2005) together with the NED data represent the peak in the optical range fitted by a thermal spectrum (dashed green line). The red solid line depicts the SSC-model curve.](https://academic.oup.com/mnras/article-abstract/401/2/973/1150279)
\[ R_\text{bh} = 2.85 \times 10^{10} \text{ cm}. \]

Considering average Sun-like stars, we yield an estimate of the number of stars responsible for this blackbody radiation given by \( R_\text{bh}/R_\odot = 1.7 \times 10^{11} \). This number together with the temperature \( T \) gives a hint for the host galaxy of 1 ES 1218+30.4 being the origin of this feature in the SED not being modelled by the SSC approach. With this blackbody approximation, we get an estimate for the central black hole mass of the AGN using the correlation given by Kormendy & Gebhardt (2001)

\[
M_{\text{BH}} = 0.78 \times 10^8 M_\odot \left( \frac{L_{\text{bulge}}}{10^{10} L_\odot} \right). \tag{16}
\]

Here, we get \( M_{\text{BH}} = 5.6 \times 10^8 \) and a corresponding Eddington luminosity \( L_{\text{Edd}} = 7.3 \times 10^{36} \). Lacking observations of the radial dependence of the surface brightness of the host galaxy, the accuracy of these estimates is not better than a factor of a few. Adopting a bulk Lorentz factor \( \Gamma = 57 \), which is consistent with \( \delta = 80 \) for reasonable angles of the jet axis to the line of sight, the injected luminosity in the AGN frame is \( L_{\text{inj}} = 4/3\pi R_\text{inj}^2 \Gamma^2 \int dy \gamma m c^2 \langle Q(y) \rangle = 7.3 \times 10^{43} \text{ erg s}^{-1} \). The resulting very low Eddington ratio of the order of 0.001 is in line with the results of population studies of BL Lac objects, for which Treves et al. (2002) find 0.01.

4 DISCUSSION

In this paper, we presented SSC-model fits to the contemporaneous data of 1 ES 1218+30.4 in the X-ray and VHE range. In the optical regime a simple blackbody spectrum has been applied to complete the model SED. In a similar way, Katarzyński, Sol & Kus (2000) modelled the optical data of Markarian 501 by applying a standard model for the elliptical host galaxy (Nilsson et al. 1999). Our simple approach to the background radiation of the host galaxy actually suffices; the more sophisticated approach of Katarzyński et al. (2001) might be of use if more data for the host galaxy would be available, but at this high redshift details are not accessible. Celotti & Ghisellini (2008) have recently studied 1 ES 1218+30.4, assuming it is in a flaring state.

Observational results for 1 ES 1218+30.4 have also been discussed in Sato et al. (2008) with special regard to the variability of the source. The authors concluded that the source must have a very hard electron distribution with power-law slope \( s = 1.7 \). We disagree with this result, as we were able to show that there exist model parameters which are well in line with relativistic shock acceleration theory (Ellison, Reynolds & Jones 1990), although harder spectra can be imagined for more extreme sources (Vainio & Schlickeiser 1998).

The major difference of our spectrum compared to Sato et al. (2008) is that we assumed the optical regime to be dominated by the host galaxy, approximately described by a blackbody spectrum. Therefore, the need for extreme electron spectra could be relaxed. Considering that the Swift, MAGIC and VERITAS data used here do not show strong flaring features, we have modelled the SED as steady-state SSC emission with our time-dependent code, obtaining physical parameters of the emission region. These parameters lie well in the range found with SSC models for other HBLs. The small magnetic field value differs slightly from the normally used values of about 0.1–0.2 G in SSC models, but in contrast to competing hadronic models this value is still reasonable.

Additionally, the central black hole mass could be estimated from the host galaxy properties, demonstrating that the emission region is consistent with a sub-Eddington jet as generally expected for BL Lac-type sources. The growing, but still marginal, discrepancy of our model SED and the VHE spectra at highest energies, if taking the expected gamma-ray attenuation due to pair production into account, is a concern. It is also found in other studies of TeV blazars. This trend could indicate an insufficiency of the SSC-model approach, a weaker than expected gamma-ray attenuation or an incomplete understanding of the energy determination of air showers from their Cherenkov emission.

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