Modelling rapid TeV variability of PKS 2155–304

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ABSTRACT

We present theoretical modelling for the very rapid TeV variability of PKS 2155–304 observed recently by the H.E.S.S. experiment. To explain the light-curve, where at least five flaring events were well observed, we assume five independent components of a jet that are characterized by slightly different physical parameters. An additional, significantly larger component is used to explain the emission of the source at long time scales. This component dominates the emission in the X-ray range, whereas the other components are dominant in the TeV range. The model used for our simulation describes precisely the evolution of the particle energy spectrum inside each component and takes into account light travel time effects. We show that a relatively simple synchrotron self-Compton scenario may explain this very rapid variability. Moreover, we find that absorption of the TeV emission inside the components due to the pair creation process is negligible.

Key words: Radiative transfer – BL Lacertae objects: individual: PKS 2155–304

1 INTRODUCTION

Among the different models proposed to explain X-ray and gamma-ray emission of TeV blazars one distinguishes two classes: the leptonic and hadronic models (e.g. Krawczynski 2004). This division depends on the assumption one makes about the particles that initially carry the energy that is to be converted into electromagnetic emission during the evolution of the source. The aim of this paper is to explain the rapid variability in the simplest possible way in order to constrain the physical parameters of the source. Therefore, we have decided to use a relatively simple leptonic scenario.

A very basic leptonic model that can be used to explain the high energy emission of TeV blazars assumes a spherical source filled with a tangled magnetic field and relativistic electrons. This source is thought to travel with relativistic velocity at a distance of less than 1 pc from the central black hole and is usually assumed to be homogeneous. The electrons inside the source produce synchrotron emission and also up-scatter part of this emission to TeV energies. This is the well known synchrotron self-Compton process (SSC) that is often applied to describe X-ray and gamma-ray observations of blazars (e.g. Bloom & Marscher 1996, Ghisellini et al. 1998, Inoue & Takahara 1999). The simplicity of this model allows to constrain some important physical parameters of the source (e.g. magnetic field strength, Doppler factor) directly from observations (e.g. Bednarek & Protheroe 1997, Tavecchio et al. 1998, Katarzynski et al. 2001). On the other hand, some uncertainty remains in such estimations because the model is too simple; it does for example not take into account significant processes such as the particle evolution inside the source or light crossing time effects (hereafter LCTE). Therefore it is very important to analyse not only the emission observed at a given time but also the evolution of the emission, especially during the periods of activity. This may provide additional constraints for the models and result in a more precise estimation of the physical parameters.

Several leptonic models have been proposed to explain the time-dependent emission of TeV blazars (e.g. Dermer et al. 1997, Kirk et al. 1998, Coppi & Aharonian 1999, Chiaberge & Ghisellini 1999, Kataoka et al. 2000, Sokolov et al. 2004). So far, no model is able to precisely describe SSC emission of an inhomogeneous or even a homogeneous source. The main problem appears in the description of the synchrotron radiation field inside the source that is inhomogeneous even in a spherically homogeneous slowly evolving source (Gould 1979). Moreover, this radiation field depends on the particle energy distribution and the particle energy distribution depends in turn on the radiation field. This is certainly only true if the energy density of the radiation field is comparable to or larger than the energy density of the magnetic field, but this condition is fulfilled in TeV blazars. Finally, very rapid variability time scales are usually assumed to be comparable to the light crossing time at the source. This means that LCTE must be
taken into account in calculations of the inverse-Compton scattering. In other words, the radiation field at a given time and a given position inside the source depends not only on the local physical conditions, but also contains photons from other parts of the source. These photons were already created at an earlier time and have propagated to the observed position. We will call this process internal LCTE. This effect is especially important for the calculation of the inverse-Compton emission and somewhat less for the synchrotron emission (although the radiation field has generally also an impact on the evolution of the electron energy spectrum). The internal LCTE was taken into account for the first time in the model proposed by Sokolov et al. (2004). However, this model assumes dominance of the energy density of the magnetic field over that of the radiation field. In this case the impact of the radiation field on the electron energy spectrum is negligible.

A second LCTE, which we call external, is equally important for both the synchrotron and the inverse-Compton emission. The external observer receives at a given time the emission produced by different parts of the source at different times in the comoving frame of the source. This is due to the different travel times that photons from different parts of the source need to reach the observer. If the emission level of the source does not change, the observer will always receive the same amount of radiation; if it changes on long times scales, differences in photon travel times can be neglected. However, if there is a change of the emission level with a duration shorter than the light crossing time of the source, the different travel times of the photons must be taken into account. One of the first attempts to account for this effect was made by Chiaberge & Ghisellini (1999). It should be noted that in their model they neglected internal LCTE, which is a good enough approximation under certain conditions, as we will explain below in the description of the model.

Another important problem in time dependent SSC modelling is the description of the particle acceleration and evolution of the particle energy spectrum. It is widely believed that the particles are accelerated by shock waves created by colliding components of a jet. In such collisions, some fraction of the kinetic energy related to the bulk motion of the components is transformed into random kinetic energy of the particles. This energy is then radiated away. The acceleration and evolution of the spectrum are usually described by the kinetic equation, which is a partial differential equation (e.g., Kardashev 1962). There are two general approaches to describe the acceleration in the equation.

In the first approach, the acceleration term in the equation describes the process inside a shock wave. This approach was used for example by Kirk et al. (1998), where the evolution of the source was represented by two kinetic equations. The first equation described the acceleration inside the shock and the second the evolution of the particle spectrum in the downstream region of the shock. Particles were escaping into this region after the acceleration, creating a source for electromagnetic emission. However, this is a rather complex approach and was applied only for the synchrotron emission.

The second approach is simpler. There is no acceleration term, i.e., no description of the acceleration process. Instead, an “injection term” defines directly the result of the acceleration. One assumes a particle energy spectrum created by a hypothetical shock and describes it with a few free parameters. This approach was used for example in the model proposed by Chiaberge & Ghisellini (1999), where different types of injection were investigated.

Since there is no perfect solution for modelling of variability in the framework of the leptonic SSC scenario, we have chosen here the relatively simple model proposed by Chiaberge & Ghisellini (1999). The model, as we will show, provides very reasonable results while using only a minimum number of free parameters.

## 2 RAPID VARIABILITY

High energy variability of TeV blazars has been observed many times by orbiting X-ray experiments, as well as ground based gamma-ray telescopes. One of the most spectacular states of high activity was observed in Mrk 501 in 1997. The emission level and the spectrum of the emission changed dramatically in a period of a few days (Catanese et al. 1997, Pian et al. 1998, Diomani et al. 1998, Krawczynski et al. 2003). Very rapid variability at time scales of only a few hours was first observed simultaneously in X-rays and TeV gamma rays in Mrk 421 and reported by Maraschi et al. (1999). Today Air Cherenkov Telescopes like H.E.S.S. or MAGIC achieve major breakthroughs with minute-scale observations in the VHE range.

PKS 2155–304 has been intensively observed during the last years by different instruments, showing variability at time scales from several months to a few hours. For example Giommi et al. (1998) observed X-ray activity of this source with a variability time scale of a few hours. Similar time scales of the X-ray activity were also reported by Chiappetti et al. (1999) and Edelson et al. (2001). Observations made by Tanihata et al. (2001) show X-ray flux variations at time scales of about one day. In the TeV range, the source has been detected by the Durham Mk VI telescopes (Chadwick et al. 1999). This detection remained confirmed until observations were made by the H.E.S.S. experiment in 2002 and 2003 (Aharonian et al. 2005). Variability on daily time scales was observed during that period.

Recently (28th of July 2006, i.e. MJD 53944), a huge TeV outburst of PKS 2155–304 has been observed by the H.E.S.S. experiment (Aharonian et al. 2007). The TeV emission level of the source changed by a factor of about 20 within the observational period of about 1.5 h. Variability with a time scale of only a few minutes could be observed, which presents the fastest variability ever seen in a blazar. Unfortunately, there are no simultaneous X-ray observations that could give us strong constraints on the emission process during this first huge outburst. After this outburst, the source was being monitored by several experiments and especially almost continuously by the UVOT, XRT and BAT experiments on board the Swift satellite (Foschini et al. 2007) for a duration of several days (from 29th of July to 22nd of August 2006, i.e. MJD 53945 to MJD 53969). The comparison of the Swift data with the observations made by H.E.S.S. at that time (Raue 2008) shows a rather minor change of the UV–X-ray emission level (see Fig. 3 in Foschini et al. 2007), and a huge variation of the TeV emission. Compared to most observations
of blazars, this is a rather unexpected behaviour; however, even more extreme events, so-called orphan TeV flares, have already been observed in other sources (Krawczynski 2004, Blazejowski et al. 2005). We will in the following try to explain this rapid TeV variability event in order to constrain the physical parameters of the source.

3 THE MODEL

Here we use the model proposed by Chiaberge & Ghisellini (1999). They assume that the source of VHE emission is created by a shock wave that accelerates the electrons. The shock is perpendicular to the jet symmetry axis and moves with constant relativistic velocity ($v_s$). The particles accelerated by the shock up to extremely relativistic energies escape into the downstream region of the shock, where they generate most of the synchrotron and IC radiation. In other words the shock is injecting relativistic particles into some volume where most of the particle energy is dissipated by radiative processes. Therefore, this volume is equivalent to the source volume. For sake of simplicity, the cross section of the shock front perpendicular to the jet symmetry axis is assumed to be square, of scale $R$. The thickness of the shock front (parallel to the jet axis) is $r \ll R$. The shock is accelerating the particles and thus creating the source for a duration of $\Delta t_s = R/c$. Such an assumption eliminates the duration of the acceleration process as a free parameter and yields a final volume of the source of $R^3$. The evolution of the source is also simulated after the injection phase for a few crossing times up to almost complete decay of the X-ray and the $\gamma$-ray emission.

The source volume is divided into $10 \times 10 \times 10$ smaller cells and calculations are performed in time steps of $\Delta t' = 0.1 R/c$. This allows to take into account the external LCTE, which is the main advantage of the model. In the first step, at time $t' = \Delta t'$, only a narrow region just after the shock (at the distance from 0 to $v_s'\Delta t'$) is filled up by particles. In the next step ($t' = 2\Delta t'$) the particles injected during the first phase are somewhat “older” which means they have already lost some fraction of their energy. They are located at a distance between $v_s'\Delta t'$ and $2v_s'\Delta t'$. It should be noted that, when solving the kinetic equation that describes the evolution of the particle energy, we assume that the injection process works only during a time $t_{\text{inj}} = 0.1 R/c$, necessary to create a cell. Moreover injection is only active in the cells that are next to the shock front; for other cells we calculate only radiative cooling. The shock is creating continuously new cells filled by “fresh” particles, whereas old cells are moving systematically to larger distances. However, what is observed in the comoving frame is significantly different from this due to LCTE. The observed spectrum is produced by the electron distribution at different stages of evolution. Therefore, to obtain the total emission, it is necessary to sum up the different contributions of different cells in a specific way, as described in details in the original paper.

The source is observed at an angle $\theta = 1/\Gamma$ [rad], where $\Gamma$ is the Lorentz factor that describes bulk motion of the source. This means that in the source’s comoving frame the emission is observed at 90 degrees with respect to the jet symmetry axis and the shock velocity vector. For such an angle the external LCTE has the strongest impact on the evolution of the observed emission. Note that for zero degree the external LCTE is negligible.

Chiaberge & Ghisellini (1999) tested a few different types of injection spectra, here we use only the very simple single power-law injection $Q(\gamma) = Q_0 \gamma^{\gamma_0}$ for $\gamma_{\text{min}} \leq \gamma \leq \gamma_{\text{max}}$, where $\gamma$ is the Lorentz factor that describes the energy of the particle. We neglect also a possible escape of the particles from the source. In principle the particles may escape into regions of the jet where the magnetic field strength is significantly lower in comparison to the field inside the source. Therefore, synchrotron emission from such regions should also be significantly lower and thus negligible. However, if the radiation field outside the source is high enough, the escaped particles may still produce a significant amount of emission through IC scattering. This is a quite complex scenario with additional free parameters not yet constrained by the data. Therefore, for sake of simplicity, we neglect here any possible escape. Moreover, we have also introduced some small improvements to the model. We apply a more precise description of the IC emissivity, which uses the Compton kernel computed by Jones (1968). The kernel describes scattering on an isotropic distribution of soft photons, considering the full Klein-Nishina cross section in the head-on approximation (e.g. Inoue & Takahara 1996, Sauge & Henri 2004, Moderski et al. 2005). The cooling rate ($\dot{\gamma}$) due to IC scattering is calculated more precisely than in the original model, using the Compton kernel mentioned above (e.g. Sauge & Henri 2004, Moderski et al. 2005). We calculate the absorption of the TeV emission inside the source due to electron-positron pair production using the approximation derived by Svensson (1987) (e.g. Inoue & Takahara 1996). The absorption is calculated separately inside each cell and absorption caused by the surrounding cells during the propagation of the emission from a given cell toward the observer is also taken into account. To correct the intrinsic TeV spectra for the IR extragalactic absorption, we use an optical depth derived by Stecker et al. (2000) with the appropriate correction (Stecker et al. 2007), which was calculated in a $\Lambda$CDM universe for $h = 0.7$, $\Omega_{\Lambda} = 0.7$ and $\Omega_m = 0.3$.

There are several clear advantages to this model. The most significant one lies in the reduction of the number of free parameters needed to fully describe a single flaring event. For single power-law injection we need in principle four free parameters: minimum and maximum energy ($\gamma_{\text{min}}$, $\gamma_{\text{max}}$), density of the injected particles ($Q_0$) and index of the power-law ($n$). However, precise values of $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$ are not crucial for the model. To provide a significant amount of low energy synchrotron photons for the IC scattering, it is indeed sufficient to keep $\gamma_{\text{min}}$ relatively small (e.g. $1 \leq \gamma_{\text{min}} \leq 10^3$). On the other hand, the value of $\gamma_{\text{max}}$ inside each cell at a given time is precisely calculated according to the cooling conditions inside the source. Therefore, it is sufficient to assume $\gamma_{\text{max}}$ high enough to be able to produce TeV gamma-rays. Simulating the emission of six different sources we then use $\gamma_{\text{min}} = 1$ and $\gamma_{\text{max}} = 10^6$. The index of the injected spectrum, $n = 2$, is the same in all our calculations. Three more free parameters are required to completely describe a single source: the source extension ($R$), the magnetic field strength inside the source ($B$), and the Doppler factor ($\delta$). This results in 7 free parameters, a number identical to the one required in the simple stationary scenario (see the introduction). However, if this simple
scenario uses a broken power-law particle energy distribution (this is required in most cases) then the number of free parameters increases to 9. Moreover, it is not clear how such a broken power-law energy distribution could be created when for example the spectral index above the break is \( n + 1 \). On the other hand, the model we use requires only a single power-law injection to provide a self-consistent explanation for the observed X-ray spectra that one could approximate by broken power-law functions. Such broken synchrotron spectra are created by external LCTE. This is another advantage of the model and this shows also that the observed index of the synchrotron emission may have nothing to do with the index of the particle energy distribution inside the source. Since \( \gamma_{\text{min}}, \gamma_{\text{max}} \) and \( n \) have the same values in all our calculations and minimal impact for the result of the modelling, we are left with only four important parameters \( (Q_0, B, R, \delta) \) that describe the evolution of a single source. In comparison to the nine parameters required by the simple stationary scenario, this is a quite simple description for a single activity event. This is important when one has to explain several flares one by one.

The model does not describe internal LCTE, which is the main drawback of this scenario. However, this effect is not very important in the case where single power-law particle energy distribution is injected. After the injection, the particle energy spectrum inside the cells is modified only by radiative cooling that is systematically reducing \( \gamma_{\text{max}} \). This means that the synchrotron emission produced by the most energetic particles is also systematically reduced. However, this emission contributes little to the IC scattering due to the Klein-Nishina restriction. On the other hand, the synchrotron emission produced by the particles with medium and low energies remains unaffected by the cooling for a relatively long time. Thus the synchrotron emission produced by those particles remains equal and constant inside most of the cells and is largely responsible for the IC scattering.

4 RESULTS

There are no X-ray observations simultaneous with the rapid variability observed by H.E.S.S. on the 28th of July 2006. Therefore, to constrain the model we decided to use the data obtained by Swift during the several day long campaign of observations that was triggered by this rapid TeV activity. The X-ray light curve and spectrum does not show a significant change of the emission level, whereas TeV observations \cite{Rand2008} shows a dramatic change of the TeV emission level during this campaign. Thus, we decided to simulate an event where X-ray emission remains almost constant during the TeV flaring activity. As we already mentioned such activity was already observed at least two times in other TeV sources.

However, such a situation is problematic for SSC modelling, where the synchrotron emission that provides low energy photons for the IC scattering should usually vary as much as the IC emission. Only in the quite unrealistic case where only the particle density inside the source is varying may the IC emission increase or decrease as the square of the synchrotron emission \( F_{\text{IC}}(\nu, t) \propto [F_{\text{synch}}(\nu, t)]^2 \). However, this anyway may be diluted by the LCTE \cite{Katarzynski2005}. The simple solution for this problem is to assume that the X-ray emission is dominated by a relatively large component from a jet that provides almost constant emission on a time scale of several days. Since the density of such a large component is relatively low, the level of the TeV emission must also be negligibly low. The existence of such a component is strongly supported by the observations made by Swift, where for several days a nearly constant emission level was observed. The H.E.S.S. observations show that, in addition, relatively small components can appear inside the jet. These components may not be strong enough to be dominant in X-rays, but may be very compact and therefore very strong in the TeV range.

We simulate in our model one large jet component (we call it background component because it is not visible in the TeV range), and five small components (here called foreground components) dominant at TeV energies. The main difference between the background component and the foreground components appears in the estimate of the size and the particle density. Moreover, the small components are likely located at a distance of less than 1 pc from the center, whereas the large component should be located further downstream in the jet, a few parsec from the center.

In Fig. 1 we show the light curve and average spectrum obtained by H.E.S.S. on MJD 53944 as well as the spectra obtained by Swift a few days later. We also show in this figure the results of our calculations, where rapid TeV variability is well reproduced by the superposition of the IC emission of the five foreground jet components (denoted \( c_{2-6} \)). Note that the IC emission of the background component \( (c_1) \) is negligible in the TeV energy range. On the other hand, this component dominates the emission in the X-ray range. We show a theoretical light curve calculated in the Swift energy range 0.3–10 keV, where emission from the background component appears to be almost constant in the relatively short time interval (2.5 h) presented in the figure. The total duration of the background component activity, which is calculated in the same way as the activity of the foreground components, is about 15 days. This long term activity starts 10 days earlier than the first foreground component \( (c_2) \) flare. Finally, we show synchrotron and IC spectra calculated for two arbitrarily selected times (MJD 53944.035 and 53944.049) that correspond to medium and high TeV emission levels. Note that the calculated spectra

| name | \( c_1 \) | \( c_2 \) | \( c_3 \) | \( c_4 \) | \( c_5 \) | \( c_6 \) | unit |
|------|------|------|------|------|------|------|------|
| \( \delta \) | 20 | 30 | 30 | 30 | 30 | 30 | |
| \( B \) | \( 3 \times 10^3 \) | 5.2 | 3.5 | 4 | 2.3 | 6 | \( 10^{14} \) cm |
| \( t_{\text{inj}}Q_0 \) | \( 8 \times 10^{-6} \) | 3.2 | 7.95 | 6.8 | 12 | 2.45 | \( 10^7 \) cm \(^{-3} \) |
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Figure 1. Activity of PKS 2155–304 observed by H.E.S.S. (Aharonian et al. 2007) & Swift (Foschini et al. 2007) in July and August 2006 and results of our modelling. Panel a) shows the rapid variability observed by H.E.S.S. and the calculated light curve (thick solid line), where the contributions from simulated jet components ($c_2$–$c_6$) are indicated by thin solid lines. A theoretical light curve has also been calculated in the X-ray range (panel b). Here, an extended, slowly evolving jet component ($c_1$) dominates the emission over the other jet components. Sub-panels c) and d) show the observed average spectrum in the TeV range and two spectra obtained by Swift a few days later. In the sub-panels, we also show spectra calculated for two arbitrarily chosen times (MJD 53944.035 and 53944.049) corresponding to medium (c) and high (d) TeV emission levels. The solid lines in the sub-panels show the total emission; the dashed lines indicate contributions from individual components. One can see that the background component ($c_1$) dominates in the X-ray range, whereas the foreground components (here $c_2$ and $c_4$) dominate the emission in the TeV range. Calculated not absorbed intrinsic TeV spectra are indicated by dotted lines.

are not well constrained, since we have only an average observed TeV spectrum and no simultaneous X-ray observations. Detailed values of the physical parameters used for the calculations are given in Tab. 1. Note that in order to precisely explain the TeV light curve we had to modify only the sizes of the small sources that is constrained by the observed variability time scales and the particle injection rate to explain correctly the level of the emission.

Rapid variability requires a relatively small and dense source, which may be optically thick for TeV emission due to pair production inside the source. The simplest solution for this problem is to assume a relatively large value of the source Doppler factor ($\delta \gtrsim 50$), which decreases the observed variability time scale and increases the observed emission level. However, such a large value of the Doppler factor might also significantly increase the scattering of electrons inside the source on the external ambient radiation field. Therefore, the external IC scattering might become the dominant process that produces most of the TeV emission. Such a scenario was recently proposed by Begelman et al. (2007). However, the efficiency of the external IC scattering depends on the intensity of the radiation field and also on the distance from the center where the source is created. It may be possible that the intensity is too low and the distance is too large for this process to be important, as has usually been assumed in the modeling of the TeV blazar activity up to now.

An alternate scenario to the external IC scattering was
proposed recently by Ghisellini & Tavecchio (2008). They assume that a fast jet ($\delta \lesssim 30$) contains even faster moving compact sources ($\delta \gtrsim 50$). The radiation field produced by the jet is amplified in the comoving frame of the compact sources due to the difference in velocities, which increases the IC emission produced by these sources. However, measurements of the motion of parsec-scale jet components in PKS 2155–304 at radio frequencies suggest a value of the Doppler factor of a few (Piner & Edwards 2004).

We have carefully calculated the absorption due to pair production inside the source using a moderate value of the Doppler factor ($\delta = 30$). We found this process to be negligible in our approach. There are two reasons for this. First, the variability time scale that we are trying to explain is still relatively long (10–15 minutes), and second, more importantly, in all our calculations of the emission from small sources, the synchrotron emission level is significantly lower than the IC radiation level. It should be noted that we have also verified that by trying to explain a variability time scale of about 5 minutes, as well as by trying to keep $vF_{\text{syn}, \text{X-ray}} \lesssim vF_{\text{IC, TeV}}$ that is frequently observed in TeV blazars, we may obtain significant absorption of the TeV emission. Our results show that the classical SSC approach used frequently to explain emission of TeV blazars can also explain rapid TeV variability if we assume that the X-ray emission is dominated by an extended, slowly evolving source.

5 CONCLUSIONS

We have shown in this paper that the rapid TeV variability of PKS 2155–304 can be well explained using a standard SSC approach while taking into account the particle evolution and the external LCTE. In our approach the internal LCTE is of minor importance. The model we use requires in principle four free parameters to describe a single activity event. Therefore, we may compare the physical parameters derived from such modelling with the parameters derived from previous estimations of blazar emission (e.g. Tavecchio et al. 1998). This shows that our parameters are similar to other results (e.g., $B \lesssim 0.1$ G and $\delta = 20 \rightarrow 30$); only the size ($R \approx 5 \times 10^{14}$ cm) of the small sources is about one order of magnitude smaller than the values estimated so far.

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