

## Revisiting the rapid VHE gamma-ray flare of PKS 2155-304 in a multi-blob model

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Blazars, a subclass of active galactic nuclei (AGN), are known to be bright  $\gamma$ -ray sources, frequently exhibiting active (flaring) periods. The blazar PKS 2155-304 is a high synchrotron-peaked BL Lac object located at redshift  $z = 0.116$ . On 2006 July 28, an extremely remarkable outburst of VHE  $\gamma$ -ray emission from this blazar was reported by the H.E.S.S. experiment, with an average flux more than 10 times the low-state level. The variability timescale of this extraordinary flare was as short as approximately 200 s. In order to guarantee the transparency of the emission region for TeV photons, the fast variability demands an extremely high Doppler factor  $\delta_D > 50$  of the jet within the classical one-zone model, leading to the so-called “Doppler factor crisis”. Here we demonstrate that the stochastic dissipation model, which is a multi-blob scenario for blazars, can self-consistently explain the giant TeV flares of PKS 2155-304 and the low-state emission before and after the flares, in terms of both multi-wavelength spectral and variability characteristics. The required Doppler factor in this model can be as low as 20, which is a reasonable and typical value for blazar jets. The obtained model parameters may shed some light on the physical properties of the relativistic jet.

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## 1. Introduction

Blazars are the most extreme subclass of active galactic nuclei (AGN) with a relativistic jet almost pointing to the observer [1]. Blazars can be divided into flat spectrum radio quasars (FSRQs) and BL Lacertae objects (BL Lacs) based on whether there is strong broad-line emission in the optical and ultraviolet band. It basically depends on the accretion rate of the black hole and the disk luminosity. Due to the Doppler boosting, the radiation of a blazar is considered to be dominated by the non-thermal radiation of relativistic particles in the jets. The broad band spectrum displays a typical double-hump structure [e.g. 2], the origin of which are thought to be synchrotron radiation and Inverse Compton scattering in a leptonic scenario. For blazars, intense temporal variability, such as flare, is another important feature, providing insight into the microphysical process in the jet.

PKS 2155-304 is a high synchrotron-peaked BL Lac with redshift  $z = 0.116$ . It is one of the brightest extragalactic X-ray sources [e.g. 3] and is identified as a TeV  $\gamma$ -ray emitter [e.g. 4]. On 2006 July 28 (MJD 53944), an extreme outburst of VHE  $\gamma$ -ray emission of PKS 2155-304 was reported by H.E.S.S. [5]. During this extraordinary outburst, the VHE flux exhibited amplitudes ranging from 0.65 to 15.1 times the Crab Nebula flux (denoted by  $I_{\text{Crab}}$ ) above 200 GeV, with an average flux  $7I_{\text{Crab}}$  — more than 10 times the typically observed value of  $0.15I_{\text{Crab}}$ . Well-resolved sub-flares exhibited variability timescales as short as 200 s, implying that the size of the emission region must be exceptionally small,  $R \lesssim 5.4 \times 10^{13} \delta_1$  cm (where  $\delta_1 = \delta_D/10$  and  $\delta_D = 1/\sqrt{1 - \beta_\Gamma \cos \theta_{\text{obs}}}$  is the Doppler factor, with  $\Gamma$  being the bulk Lorentz factor of emitting material moving along the jet at an angle  $\theta_{\text{obs}}$  with respect to our line of sight). In the night of 2006 July 29 (MJD 53945), another significant  $\gamma$ -ray outburst took place 44 hours after the first outburst [6]. The  $\gamma$ -ray flux reached 11 times the Crab flux above 400 GeV of the major flare and several main sub-flares were detected within a few hours. Except for these two outbursts, the source experienced a relatively low flux state in the night between the two dramatic events [7]. These observations revealed both the long-term evolution and the fast variations of this TeV blazar.

A widely used and classical model to study the spectrum and variability of blazars is the one-zone leptonic model [e.g., 8]. It is assumed that all the non-thermal radiation of a blazar is generated from a compact spherical plasma blob filled with high-energy electrons inside the jet. For a flare with a variability timescale of  $\Delta t$ , the radius of the blob  $R$  need be smaller than  $\delta_D c \Delta t / (1 + z)$ , since otherwise the variability would be smeared out due to the light-travel-time difference of photons emitted from different parts of the blob. On the other hand, if the radiation zone (or the blob) is too compact, the photon density of the synchrotron radiation emitted by electrons would be very high and hence produce a high opacity for high-energy gamma-ray photons via the pair production process. Therefore, in the exceptional  $\gamma$ -ray outburst of PKS 2155-304 on 2006 July 28, if the whole emission is produced in a single compact region, an unusually high Doppler factor  $\delta_D > 50$  is needed to ensure that the VHE  $\gamma$ -ray photons are able to escape the blob [9]. This value is much higher than the one inferred from radio observations, and this is often referred to as the “Doppler factor crisis” [10].

Recently, the so-called stochastic dissipation model, a multi-blob framework, has been proposed to explain the multi-wavelength spectral energy distributions (SEDs), light curves (LCs) and polarization of blazars [11, 12]. It assumes that numerous blobs are generated along the blazar jet,

contributing to the whole radiation of the blazar. It is capable of reproducing the low-state of a blazar with a smaller  $\gamma$ -ray opacity compared to the one-zone model. In this work, following the stochastic dissipation model, we study the outburst events caused by several blobs with strong dissipation, and try to reproduce the multi-wavelength spectrum and the minute-to-hour scale variability in the case of PKS 2155-304. In particular, we will search for a solution with a relatively modest Doppler factor, aiming to avoid the Doppler factor crisis. The rest of this paper is structured as follows. In Section 2, the multi-blob framework is briefly introduced. In Section 3, we apply our model to the two outbursts of PKS 2155-304 observed on 28 July 2006 (MJD 53944) and 30 July 2006 (MJD 53946). The conclusions are presented in Section 4. Throughout the paper, we adopt the  $\Lambda$ CDM cosmology with  $H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.29$ ,  $\Omega_\Lambda = 0.71$ .

## 2. Model Description

In the stochastic dissipation model, blobs are generated in the jet persistently via random dissipation events, such as magnetic reconnection events [e.g., 13] or internal shocks [e.g., 14]. A flare will appear if a strong dissipation event occurs and accelerates an exceptionally large amount of electrons in the accompanying blob(s) compared to others. Therefore, a blazar's emission during a flare consists of the radiation from both the flaring zone and that from non-flaring zones.

Following the treatment in [12], a conical jet is assumed with a constant half-opening angle  $\theta$ . Many blobs are distributed inside the jet from a distance  $r_0$  to  $L + r_0$  away from the central super massive black hole (SMBH). The jet and blobs have a relativistic motion with the bulk Lorentz factor  $\Gamma$ . As a result of relativistic Doppler boosting, the observed emission will be significantly enhanced, characterized by the Doppler factor  $\delta_D$ . In this work,  $\theta_{\text{obs}} \lesssim 1/\Gamma$  is assumed for blazars leading to  $\delta_D \approx \Gamma$ . The radius of blobs in the comoving frame  $R'$ <sup>1</sup> is related to the transverse radius of the segment,  $R' = \kappa R_{\text{seg}}$ . Assuming conservation of magnetic luminosity along the conical jet [e.g., 15], the magnetic field is inversely proportional to the distance. Relativistic electrons are accelerated and injected into blobs over a time period  $t'_{\text{inj}}$ , which is considered to be the same as the light crossing timescale of the blob,  $R'/c$ . The injection luminosity of electrons  $L'_{\text{inj}}$  is assumed to be the same in all blobs within a segment, and the injected electron energy distribution (EED) is assumed to be a power-law distribution  $Q'(r, \gamma') = Q'_0(r) \gamma'^{-s}$ , for  $\gamma'_{\text{min}} < \gamma' < \gamma'_{\text{max}}$ . The temporal evolution of the EED in the blobs can be described by

$$\frac{\partial N'(\gamma', t', r)}{\partial t'} = -\frac{\partial}{\partial \gamma'} [\dot{\gamma}'(\gamma', t', r) N(\gamma', t', r)] - \frac{N'(\gamma', t', r)}{t'_{\text{esc}}(r)} + Q'(\gamma', r), \quad (1)$$

where  $t'_{\text{esc}}(r) = 10R'/c$  is the escape timescale.  $\dot{\gamma}'(\gamma', t', r) = -c\gamma'/R' - b'(\gamma', t', r)\gamma'^2$  is the energy loss rate, where the first term describes adiabatic losses and the second term stands for radiative energy losses caused by synchrotron and IC processes. When calculating the radiation of a single blob, the light-travel-time effect is considered. Assuming a homogeneous electrons distribution in a blob, the radiation generated by each part of the blob simultaneously will not be detected by the observer at the same time, smoothing the observed LCs. The overall emission of a

<sup>1</sup>Hereafter, quantities in the comoving frame are primed, and quantities in the rest frame are unprimed, unless specified otherwise.

blob can be written as

$$\nu F_\nu^b(E, t, r) = \frac{(2R')^{-1} \delta_D^4}{4\pi D_L^2} \int_0^{2R'} \nu L'_\nu \left[ E \frac{1+z}{\delta_D}, \left(t - \frac{x}{c}\right) \frac{\delta_D}{1+z}, r \right] dx, \text{ with } L'_\nu(t' < 0) = 0. \quad (2)$$

With the injection timescale and adiabatic cooling timescale assumed as  $R'/c$ , the active lifetime of a blob can be estimated by  $t'_{\text{blob}} = 2R'/c$  in the co-moving frame, corresponding to  $t_{\text{blob}} = 2R' (1+z)/c\delta_D$  in the observer's frame.

We define  $p(r) \propto r^{-\alpha_{\text{blob}}}$  as the probability of a dissipation event occurring per unit time and unit jet length at a distance  $r$  in the AGN rest frame.  $\alpha_{\text{blob}}$  is a model parameter which will influence the resulting SED. If  $N_b$  blobs generated in a period of time  $T$ , corresponding to a total dissipation rate  $\dot{N}_b$ , then we have  $\dot{N}_b \equiv N_b/T = \int_{r_0}^{L+r_0} p(r) dr$ . In the segment at a distance between  $r$  and  $r + \Delta r$ , the blob number is  $N_{b,r}(r) = T p(r) \Delta r$  and the locally generated blobs share the same physical properties with a small  $\Delta r$ . With the assumption of a single power-law EED at injection in the model, we further assume that the maximum electron energy (or the Lorentz factor)  $\gamma'_{\text{max}}$  is not the same among all generated blobs. Instead, it follows the distribution

$$\frac{dN_{b,r}(r)}{d\gamma'_{\text{max}}} = C(r) \gamma'_{\text{max}}^{-\alpha_\gamma}, \text{ for } \gamma'_{\text{max},1} < \gamma'_{\text{max}} < \gamma'_{\text{max},2} \quad (3)$$

where  $\gamma'_{\text{max},1}$  and  $\gamma'_{\text{max},2}$  are the lower and upper limits of the maximum electron energy, respectively, with  $C(r)$  being the normalization and  $\alpha_\gamma$  being a free model parameter. The time-averaged synchrotron spectrum of the segment can be evaluated as

$$\overline{\nu F_\nu^{\text{seg}}}(E, r) = \int_{\gamma'_{\text{max},1}}^{\gamma'_{\text{max},2}} \overline{\nu F_\nu^b}(E, r, \gamma'_{\text{max}}) \frac{dN_{b,r}(r)}{d\gamma'_{\text{max}}} d\gamma'_{\text{max}} \propto \begin{cases} \nu^{\frac{4-s-\alpha_\gamma}{2}} \int_{y_2}^{y_1} y^{\frac{\alpha_\gamma-3}{2}} e^{-y} dy & \text{for } s > 2 \\ \nu^{\frac{2-\alpha_\gamma}{2}} \int_{y_2}^{y_1} y^{\frac{s+\alpha_\gamma-5}{2}} e^{-y} dy & \text{for } s < 2, \end{cases} \quad (4)$$

where  $y = \nu(1+z)/(\delta_D \nu_B \gamma'^2_{\text{max}})$ ,  $y_1 = \nu(1+z)/(\delta_D \nu_B \gamma'^2_{\text{max},1})$ ,  $y_2 = \nu(1+z)/(\delta_D \nu_B \gamma'^2_{\text{max},2})$  and  $\nu_B = eB/(2\pi m_e c)$ . The spectral shape of a segment can be described as a smoothly connected broken power law with a high-energy cutoff, as shown in Fig. ?? . The overall emission of the jet is the superposition of the emission from each segment

$$\nu F_\nu^{\text{low}}(E, t) = \sum \nu F_\nu^{\text{seg}}(E, t, r) = \sum_i^{N_b} \nu F_\nu^b(E, t, r) \Theta(t - t_i),$$

where  $t_i$  is the starting time of the  $i$ th blob. Since the spectral shape of a segment (Eq. 4) does not depend on the distance, the total superimposed spectrum will also be described by a broken power-law. Note that in the radio band, where synchrotron self-absorption is important, the overall spectral shape is demonstrated to be  $F_\nu^{\text{low}} \propto \nu^{2-\alpha_{\text{blob}}}$  [12]. The flat radio spectrum as usually observed from blazars is obtained for  $\alpha_{\text{blob}} = 2$ .

When considering a specific outburst event composed of several flares, we introduce a number of  $N_b^f$  flaring blobs to be triggered at  $t_j^f, j = 1, 2, \dots, N_b^f$ , consecutively. The calculated LC can be written as

$$\nu F_\nu^{\text{flare}}(E, t) = \sum_{j=1}^{N_b^f} \nu F_\nu^b(E, t, r = r_j^f) \Theta(t - t_j^f), \quad (5)$$

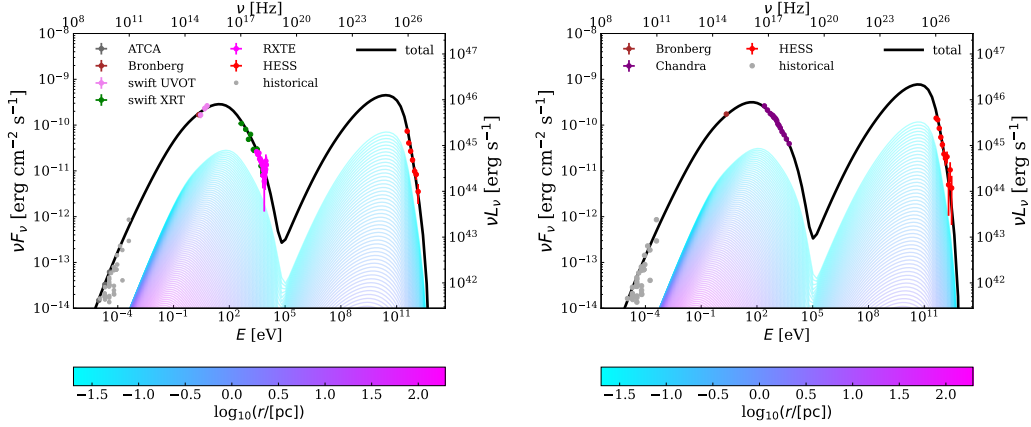


**Figure 1:** The average SEDs calculated for the two low states. The left panel corresponds to LS1, while the right panel represents LS2. The colored dots represent the observations in different energy bands as labeled in the legend. The black solid line is the overall emission generated by the jet, while the gradient color lines show the individual SEDs from each segment at different distances.

**Table 1:** Summary of low states Parameters. Disk luminosity  $L_D = 10^{42} \text{ erg s}^{-1}$ , jet base  $r_0 = 2.0 \times 10^{-2} \text{ pc}$ , jet length  $L = 200 \text{ pc}$ , half-opening angle  $\theta = 5 \text{ degree}$ , radius ratio  $\kappa = 0.3$ , total dissipation rate  $\dot{N}_b = 0.93 \text{ s}^{-1}$ ,  $\alpha_{\text{blob}} = 2.0$ .

| Free parameters                  | LS1                  | LS2                  | Notes                                                           |
|----------------------------------|----------------------|----------------------|-----------------------------------------------------------------|
| $B'(r_0) [\text{G}]$             | 0.107                | 0.080                | Magnetic field at jet base                                      |
| $L'_{\text{inj}} [\text{erg/s}]$ | $7.3 \times 10^{39}$ | $1.0 \times 10^{40}$ | Injection electron luminosity at jet base                       |
| $s$                              | 2.0                  | 2.0                  | The spectral index of electron energy distribution              |
| $\gamma'_{\text{min}}$           | $4.0 \times 10^3$    | $5.0 \times 10^3$    | Minimum electron Lorentz factor                                 |
| $\gamma'_{\text{max},1}$         | $7.0 \times 10^4$    | $1.0 \times 10^5$    | Lower limit of maximum electron Lorentz factor                  |
| $\gamma'_{\text{max},2}$         | $9.0 \times 10^5$    | $1.2 \times 10^6$    | Upper limit of maximum electron Lorentz factor                  |
| $\alpha_\gamma$                  | 2.8                  | 2.5                  | $N_{\text{blob}} \propto \gamma'_{\text{max}}^{-\alpha_\gamma}$ |

where  $r_j^f$  represents the location of the  $j$ th flaring blob. The total radiation of the jet during the outburst is  $\nu F_\nu^{\text{total}}(E, t) = \nu F_\nu^{\text{flare}}(E, t) + \nu F_\nu^{\text{low}}(E, t)$ . The average SED of a selected period of time  $T_1$  to  $T_2$  can be given by  $\nu F_\nu^{\text{total}}(E) = \nu F_\nu^{\text{low}}(E) + (T_2 - T_1)^{-1} \int_{T_1}^{T_2} \nu F_\nu^{\text{flare}}(E, t) dt$ .

### 3. Application

The first outburst took place in the early hours of MJD 53944. This outburst lasted for more than one hour and gradually decayed to a low state. The low state remained quasi-stable until midnight of MJD 53944. This quasi-stable period is chosen as the reference low state of the first outburst and is denoted as LS1. Later, another giant outburst occurred 44 hours after the first one. The gamma-ray flux of the blazar was already in the flaring state at the beginning of observation time of that night, which was around MJD 53945.85. After 4 – 5 hours of observations, the gamma-ray flux underwent a relatively slow decay process in the early hours of MJD 53946. In the period from MJD 53946.10 to MJD 53946.15, the emission reached the lowest level and was comparable to the observed flux level during the night of MJD 53946. Hence, this period is considered to be the

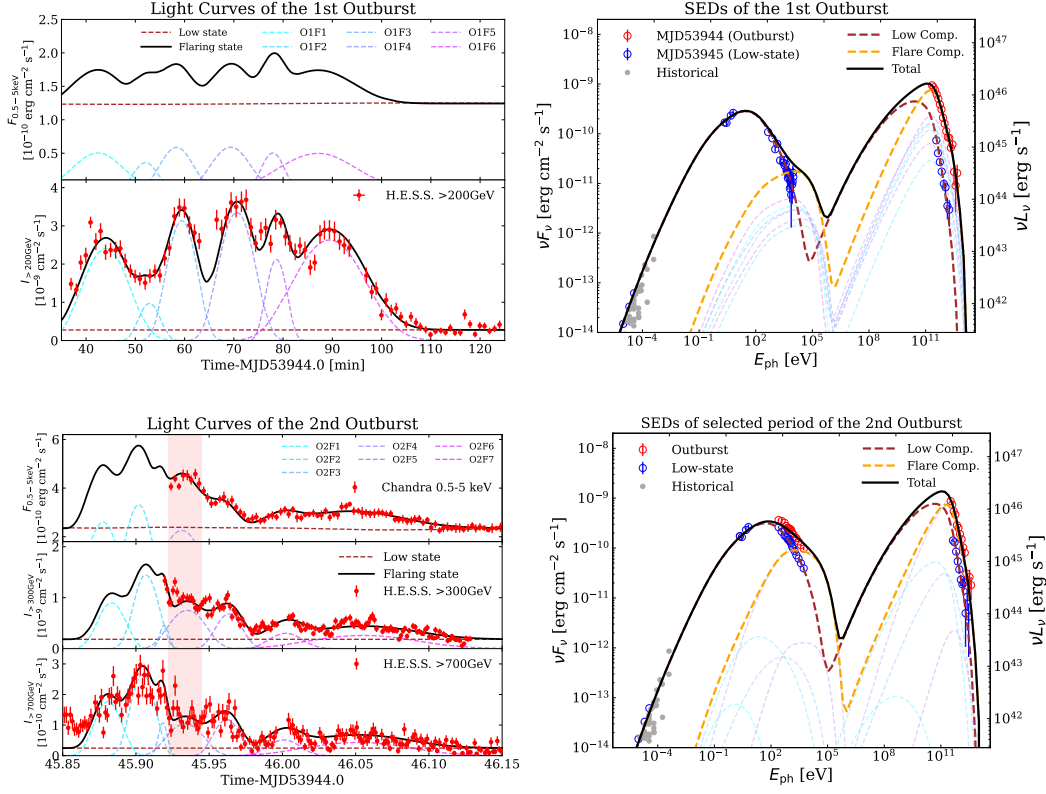


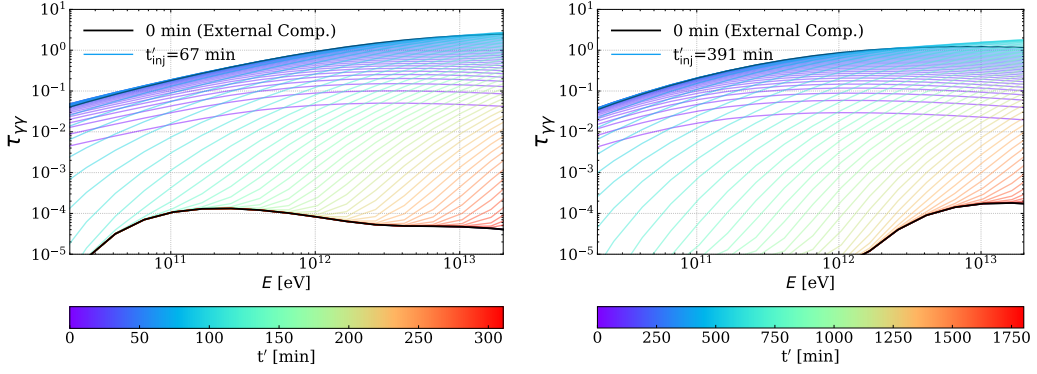
**Figure 2:** Simulated LCs (left panels) and the SEDs (right panels) during the outburst. The solid lines with gradient colors from cyan to purple are LCs (left) and SEDs (right) generated by different blobs with strong injection. In the right panels, the brown solid lines represent the SEDs of low states, the orange solid line are the averaged SEDs of selected periods during the outburst, and the black solid lines are the sum of the two components. (O<sub>i</sub>F<sub>j</sub> means the *j*th flare in the *i*th outburst.)

low state of the second outburst and is denoted as LS2. The average SED of this period is shown in right panel of Fig. 1. The model-predicted SEDs in LS1 and LS2 are displayed in Fig. 1 and the parameters are listed in Table 1. The Doppler factor of the blazar jet is fixed to be 20 in both periods.

In the first outburst, six strong dissipation events are assumed to take place, each corresponding to an identified flare. Note that there is no simultaneous X-ray observation during this period, and hence parameters cannot be well constrained. To avoid tuning too many parameters, we artificially impose some constraints on parameters. The Doppler factor is kept the same as that in the low state; the injected EED is the same for all six flares; the distance of the blobs appearing is determined by the variability timescale once the Doppler factor is fixed; the magnetic field of each small flare is imposed to be inversely proportional to the distance. Multiwavelength observations were carried out during the outburst on MJD 53946, which revealed the activity in different energy bands. This provides more restrictions on the parameters selection. We employ seven consecutive flaring blobs to fit the data. The model-predicted LCs and averaged SEDs during these two outbursts are shown in Fig. 2. Parameters for all flares are listed in Table. 2.

**Table 2:** Summary of Parameters for the flares during the two outburst, with the same Doppler factor  $\delta_D = 20$ .

| Flare | $r$ ( $\times 10^{-3}$ pc) | $R'$ ( $\times 10^{14}$ cm) | $B'$ ( $\times 10^{-1}$ G) | $L'_{\text{inj}}$ ( $\times 10^{42}$ erg/s) | $s$ | $\gamma'_{\text{min}}$ ( $\times 10^5$ ) | $\gamma'_{\text{max}}$ ( $\times 10^6$ ) |
|-------|----------------------------|-----------------------------|----------------------------|---------------------------------------------|-----|------------------------------------------|------------------------------------------|
| O1F1  | 3.3                        | 2.67                        | 0.97                       | 2.86                                        | 2.4 | 7.5                                      | 2.0                                      |
| O1F2  | 1.5                        | 1.21                        | 2.10                       | 1.15                                        | 2.4 | 7.5                                      | 2.0                                      |
| O1F3  | 2.2                        | 1.78                        | 1.46                       | 2.70                                        | 2.4 | 7.5                                      | 2.0                                      |
| O1F4  | 2.6                        | 2.11                        | 1.23                       | 3.05                                        | 2.4 | 7.5                                      | 2.0                                      |
| O1F5  | 1.5                        | 1.21                        | 2.10                       | 1.80                                        | 2.4 | 7.5                                      | 2.0                                      |
| O1F6  | 5.0                        | 4.05                        | 0.64                       | 3.80                                        | 2.4 | 7.5                                      | 2.0                                      |
| O2F1  | 9.5                        | 7.69                        | 1.10                       | 2.70                                        | 2.8 | 1.8                                      | 1.5                                      |
| O2F2  | 8.7                        | 7.05                        | 1.23                       | 3.30                                        | 2.8 | 1.8                                      | 1.5                                      |
| O2F3  | 3.0                        | 2.43                        | 0.80                       | 2.30                                        | 2.8 | 2.5                                      | 1.5                                      |
| O2F4  | 13.0                       | 10.5                        | 1.50                       | 1.80                                        | 2.8 | 0.9                                      | 1.5                                      |
| O2F5  | 9.0                        | 7.29                        | 0.88                       | 2.20                                        | 2.8 | 1.2                                      | 1.5                                      |
| O2F6  | 11.0                       | 8.91                        | 0.58                       | 1.80                                        | 2.8 | 1.0                                      | 1.5                                      |
| O2F7  | 35.0                       | 28.3                        | 0.44                       | 1.70                                        | 2.8 | 1.0                                      | 1.5                                      |

**Figure 3:** The temporal evolution of the  $\gamma$ -ray opacity of the most compact blobs. Left panel: O1F5; right panel: O2F2. Different colors of curves represent  $\tau_{\gamma\gamma}(E_\gamma)$  at different evolutionary times ranging from 0 to  $5t'_{\text{inj}}$  since the initial particle injection.

The evolution of  $\tau_{\gamma\gamma}$  of the most compact blobs (O1F5 and O2F2) during each outburst is displayed in Fig. 3. At the beginning time, the  $\gamma\gamma$  absorption is mainly due those quasi-stable radiation component such as the radiations of BLR and DT, and from those non-flaring blobs in the jet (i.e., the low-state component), as shown with the black solid curve. The opacity increases as the electron injection is being carried on, because the soft radiation field builds up by the synchrotron radiation of injected electrons. When the electron injection ceases, the synchrotron radiation field fades away. The opacity therefore decreases with time and finally returns to the level of the beginning time. We see that the highest opacity for 1 TeV photons in the flares during the evolution is smaller than unity. The averaged  $\tau_{\gamma\gamma}$  is expected to be smaller than that in the one-zone model by 1 – 2 orders of magnitude above a few hundred GeV.

#### 4. Conclusions

The two gigantic outbursts of PKS 2155-304 discovered on 28 – 30 July 2006 present extremely short timescales of sub-flares and remarkable flux enhancements in the TeV  $\gamma$ -ray band. This implies the existence of a compact high-energy emission region in the blazar jet. In the classical one-zone framework, a large Doppler factor is required to avoid absorption of TeV photons inside the compact emission region, leading to the so called “Doppler factor crisis”. In this study, we modeled the SEDs and LCs of the two outbursts of PKS 2155-304 within a multi-blob framework, the stochastic dissipation model.

In this model, the emission of the blazar during the outburst is composed of a quasi-stable low-state component which is the superposition of numerous non-flaring blobs along the jet, and a flaring component produced by a series of flaring blobs which are formed in strong dissipation events in the jet. The model can reproduce the minute-scale TeV variability with a moderate and typical value of  $\delta_D = 20$  for the blazar jet, and explain the simultaneous X-ray observations during the second outburst. The opacity due to  $\gamma\gamma$  absorption is significantly reduced compared to that in the one-zone model. This is mainly because the ultraviolet – X-ray radiation, which serves as target photons for the attenuation process, is shared among many blobs along the jet, and consequently the target photon density is significantly reduced in a single flaring blob responsible for the TeV flare. Our model provides a solution to the “Doppler factor crisis”.

Our SED and LC fits require a significantly increased electron injection luminosity, increased magnetic field in a single blob compared to the parameters for the low state. The required jet’s power  $P_{\text{jet}}$  is several times  $10^{44}$  erg s $^{-1}$  for both the low state and the flaring state, with the latter being about 30% higher than the former. This is because the number of blobs (or dissipation zones) in the low state is more numerous. The TeV flux enhancement during the two outbursts may then be understood as the formation of compact and intense dissipation zones at small distance, leading to a significant boost of the IC radiation efficiency. The average magnetization parameter of the jet, i.e., Poynting-to-kinetic luminosity ratio, is approximately 0.3 at  $r > r_0 (= 0.02 \text{ pc})$ , where dissipation events can frequently and stably occur. Assuming the dissipation is due to magnetic reconnection, we can derive the magnetization parameter of non-dissipating region of the jet is about 10, which is consistent with a magnetically driven jet.

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