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A unified model for orphan and multi-wavelength blazar flares

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Blazars are a class of active galactic nuclei which host relativistic jets oriented close to the observer's line of sight. Blazars have very complex variability properties. Flares, namely flux variations around the mean value with a well-defined shape and duration, are one of the identifying properties of the blazar phenomenon. Blazars are known to exhibit multi-wavelength flares, but also "orphan" flares, namely flux changes that appear only in a specific energy range. Various models, sometimes at odds with each other, have been proposed to explain specific flares even for a single source, and cannot be synthesized into a coherent picture. In this paper, we propose a unified model for explaining orphan and multi-wavelength flares from blazars in a common framework. We assume that the blazar emission during a flare consists of two components: (i) a quasi-stable component that arises from the superposition of numerous but comparatively weak dissipation zones along the jet, forming the background (low-state) emission of the blazar, and (ii) a transient component, which is responsible for the sudden enhancement of the blazar flux, forming at a random distance along the jet by a strong energy dissipation event. Whether a multi-wavelength or orphan flare is emitted depends on the distance from the base of the jet where the dissipation occurs. Generally speaking, if the dissipation occurs at a small/large distance from the supermassive black hole, the inverse Compton/synchrotron radiation dominates and an orphan γ-ray/optical flare tends to appear. On the other hand, we may expect a multi-wavelength flare if the dissipation occurs at a intermediate distance. We show that the model can successfully describe the spectral energy distribution of different flares from the flat spectrum radio quasar 3C 279 and the BL Lac object PKS 2155-304.

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1. Introduction

One of the most peculiar aspects of blazar variability are the so-called orphan flares. These are flares that occur in a specific energy band without correlated variability in other bands, and have been discovered in many blazars (orphan X-ray flare [e.g. 1]; orphan optical flare [e.g. 2–5]; orphan GeV flare [e.g. 5–10]; orphan TeV flare [e.g. 7]). Interestingly, different types of flares, i.e., orphan flares and multi-wavelength flares, have been observed to occur in the same blazar from time to time. For instance, the FSRQ PKS 0208-512 exhibited three flares at optical and near-infrared wavelengths within 3 years, with the second one having no γ-ray counterpart. Ref. [11] found that the Compton dominance (q), which is defined as the luminosity ratio between the IC component and synchrotron component, was different for the three flares. This was interpreted as evidence for a varying magnetic field and/or varying soft photon field during these optical outbursts.

In this work, we attempt to establish a connection between orphan and multi-wavelength flares occurring in a certain blazar, and search for a theoretical interpretation of the spectral variety of blazar flares in a unified physical picture. In general, the non-thermal blazar emission is produced when the jet's energy (magnetic or kinetic) is dissipated and transferred to relativistic particles. The properties of the resulting non-thermal emission may strongly depend on the distance of the dissipation site from the central supermassive black hole (SMBH), since the physical environment can experience a pronounced change along the jet [e.g. 11–14]. However, the location of the dissipation zone in blazar jets remains uncertain [e.g. 15–17]. In some previous studies, it was suggested that dissipation may occur stochastically along the jet of a blazar [e.g. 18–20]. In this framework, the non-flaring emission of a blazar results from the superposition of radiation produced in numerous dissipation zones. If additional energy dissipation takes place in one (or a few) of them, so that its (their) emission outshines the rest of the jet, then the blazar is expected to flare. Therefore, there may be no essential difference between the non-flaring state and the flaring state of a blazar, except that the flaring state is related to a much stronger dissipation event. The distance of the flaring zone to the SMBH can then determine the spectral and temporal properties of the flare. In this paper, we explore in detail such a scenario. Hereafter, we refer to it as the stochastic dissipation model.

2. Model Setup

We assume that the emission of the blazar jet in a flaring state is composed of at least two emission components. One component arises from a flaring zone that dominates the flare emission. The appearance of such component may be related to MHD instabilities [21, 22] or magnetic reconnections in the jet [23–27]. The other component is the superposition of emission from numerous but comparatively weak dissipation zones along the entire jet. The latter can be regarded as a background emission to the flare [e.g. 28] and might describe the non-flaring blazar emission. The two emission components are assumed to to be decoupled from each other. Since we focus primarily on the former component in this work, the modelling of the background radiation spectrum is simply characterized with a polynomial function.

In Fig. 1 we show a sketch of the considered scenario. Since the ratio between the power of the synchrotron radiation and the power of the IC radiation is roughly proportional to the ratio between

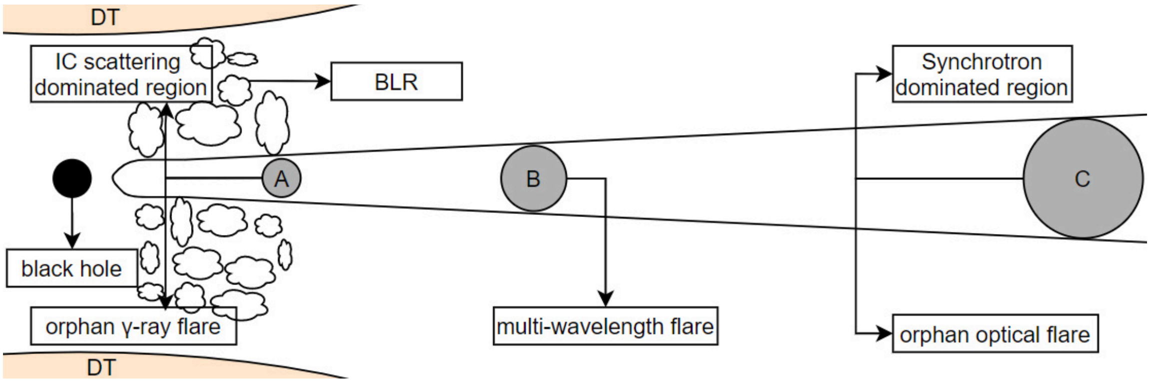

Figure 1: Schematic view (not to scale) of the stochastic dissipation model. DT and BLR represent dusty torus and broad-line region respectively. The background radiation comes from numerous but relatively weak dissipation zones (not shown here). The flaring zone (indexed blobs) occurs at a random distance from the base of the jet. We argue that the orphan γ-ray flares are more likely to arise, if the flaring zone occurs in location A. The orphan optical flares may arise if the flaring zone occurs in location C, while multi-wavelength correlated flares are expected in location B.

the energy density of the magnetic field $u_{\rm B}$ and that of the target radiation field $u_{\rm ph}$, the emission from the flaring zone will be dominated by the IC process if it occurs relatively close to the SMBH, given the presence of the broad line region (BLR) and/or the dusty torus (DT). As a result, the γ-ray emission from the flaring zone may exceed that of the jet's background emission, while the synchrotron radiation of the flaring zone at lower frequency could still be subdominant. In this case, the blazar's emission is enhanced specifically at the γ-ray band, and the blazar appears to be experiencing an orphan γ-ray flare. As the distance of the flaring zone to the SMBH increases, the synchrotron radiation becomes increasingly important with respect to either SSC or EC radiation. The synchrotron process could dominate if the dissipation takes place beyond a certain distance and an orphan optical flare may then be expected.

3. Application to 3C 279 and PKS 2155-304

Blazars are historically divided in two classes, namely FSRQs and BL Lacs, according to their optical spectra. The former display strong, broad emission lines, while the latter show at most weak emission lines, and in many cases are completely featureless [29]. These sources are thought to be powered by accretion disks with different mass accretion rates and radiative efficiencies (for a review, see Ref. [30]). As a result, the strength of ambient photon fields in these blazar subclasses is expected to be very different.

3C 279 is a very bright and highly variable blazar at all wavelengths. It is classified as an FSRQ at redshift of 0.536. An orphan γ-ray flare was reported on 20 Dec 2013 [6]. PKS 2155-304 is a well-known blazar in the southern hemisphere and also has bright and variable emissions, particularly in γ-ray energies. It is a relatively nearby high synchrotron-peaked (HSP) BL Lac object at redshift of 0.116. An orphan optical flare lasting a few months was reported for PKS 2155-304 in 2016 [3]. In addition to the orphan flares, many multi-wavelength correlated flares are observed in both sources. Thus, they are ideal test beds for our model.

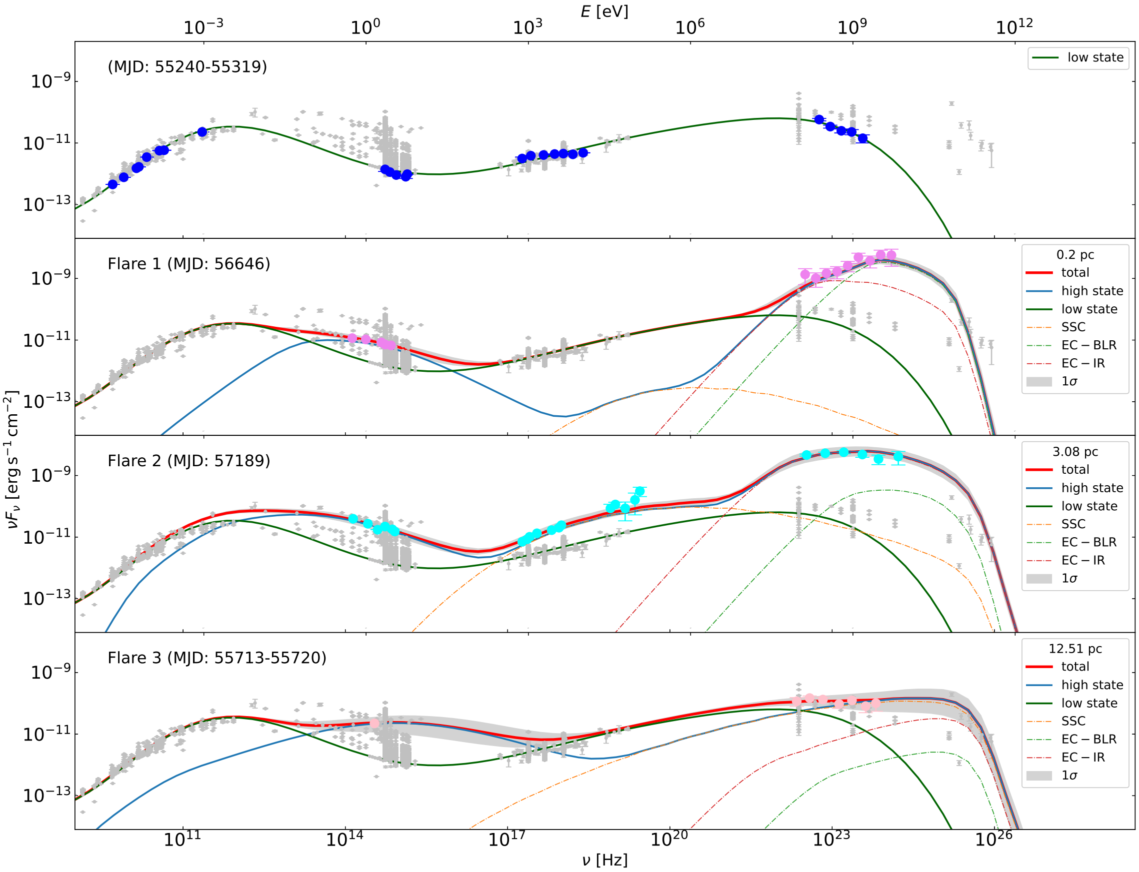

Figure 2: The fitting results for 3C 279. The green solid lines represent background radiation from many dissipation zones, and the red solid lines are total radiation including background radiation and the emission from a flaring zone. The blue solid lines represent the total emission from the flaring zone. The dot-dashed lines are IC emission from the flaring zone for different seed photon fields (see inset legends). The grey points show archival data, and the colored symbols show the data points that correspond to the three different states of 3C 279.

Fig. 2 shows the data and best-fit models of four different states of 3C 279. The grey points are historical data which come from the SSDC SED builder[1]. The blue points in the first panel are low-state data collected from February to May of 2010 (period H in Ref. [31]). The violet points in the second panel show the SED of the orphan γ-ray flare (Flare 1) in 2013 as reported by Ref. [32]. The cyan and pink points in third and fourth panels are multi-wavelength flaring state data collected on 16 June 2015 (Flare 2) and 1-8 June 2011 (Flare 3), respectively [33]. The optical flux of the latter two flares is comparable but the γ-ray flux of Flare 3 is significantly lower than that of Flare 2. The green curve in each panel is the polynomial function characterizing the background emission (low state) component. The solid blue curve shows the flare emission (high state) component. The solid red curve represents the sum of these two components.

Fig. 3 shows the data and our best-fit models of four different states of PKS 2155-304. The gray points are the sum of historical spectral data. The blue points in the first panel are non-flaring

[1]https://tools.ssdc.asi.it/SED/

data collected in 2013. The violet and cyan points in the second and third panels show the spectra during a multi-wavelength flare reported in 2014 (Flare 1) and 2015 (Flare 2) respectively. The pink points in the fourth panel give the spectrum measured during an orphan optical flare in 2016 (Flare 3) [3]. Note that the very high energy data of PKS 2155-304 are EBL corrected so we only consider the γ-ray opacity due to the radiation of the blazar jet.

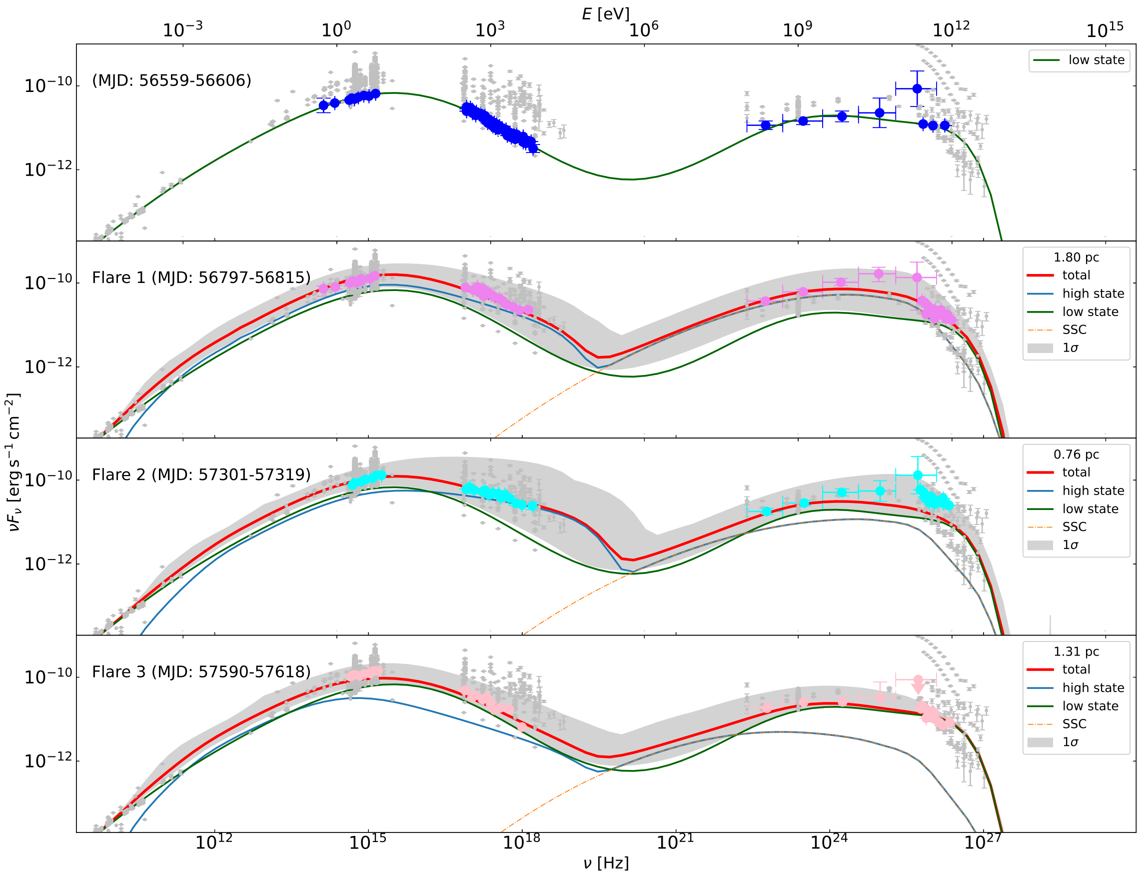

Figure 3: Same as Fig. 2 but for PKS 2155-304.

As a BL Lac object, PKS 2155-304 is not expected to have strong BLR and DT radiation. Indeed, no emission line is observed in its spectrum, posing an upper limit of 1.1×10^{41} erg s^{-1} on its BLR luminosity. Therefore we simply do not take into account any external radiation field.

4. Discussion and Conclusion

To produce an orphan flare in a certain energy band within our model, the flux of the flaring zone in that energy band should significantly exceed the flux of the background emission, while the flux in any other energy band should remain below the background emission by definition. Therefore, the key to produce an orphan flare, provided a sufficient flux from the flaring zone can be produced, is the comparison between the shape of the flaring zone's SED and that of the background emission's SED. The main feature of the double-humped-shaped SED is the relative amplitude of the two humps, which can be described by the Compton dominance q. The ratio between the Compton dominance of the flaring zone q and that of the jet's non-flaring emission, which we hereafter denote as χ, determines the type of the blazar flare. Blazars tend to present an orphan γ-ray flare if $\chi \gg 1$. On the contrary, an orphan optical flare would appear if $\chi \ll 1$. If the Compton dominance of the flaring and quiet state are comparable, a multi-wavelength flare is most likely to be produced within our model.

For FSRQs, the Compton dominance ratio χ would be much larger than unity (corresponding to orphan γ-ray flare) when the dissipation occurs comparatively close to the SMBH (e.g., $r \lesssim 1$ pc), while the ratio would be much smaller than unity (corresponding to orphan optical flare) when the dissipation occurs far away from the SMBH (e.g., $r \gtrsim 10$ pc). For BL Lacs, the situation becomes more complex due to the KN effect. A dedicated study is needed to elucidate the influence of the KN effect in the this case.

In this work we only consider the radiation of electrons in the jet. In principle, protons can be also accelerated in the dissipation zone and radiate neutrinos via the hadronic interactions with the radiation field in blazars. Indeed, an orphan neutrino flare from TXS 0506+056 was reported by the IceCube Neutrino Observatory [34]. In the work of Ref. [35] it was shown that the neutrino flare may have been produced by a dissipation event occurring at the jet base where the external radiation field is dominated by the X-ray corona of the SMBH. This interpretation is consistent with our model.

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