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An analytical hadronic synchrotron mirror model for blazars - Application to 3C279

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On the 28th of January, an orphan very-high-energy gamma-ray flare from 3C279 was detected, not accompanied by flaring in the adjacent GeV gamma-ray regime. Orphan flares have to be caused by different processes than normal γ-ray flares. Specifically, the Hadronic Synchrotron Mirror Model has been proposed to provide a consistent explanation of this flare. The expected target photon densities have been calculated analytically using the cloud/mirror model starting from basic physical principles. This is compared to the density required to produce a very-high-energy γ-ray output from $p\gamma$ induced cascades approximately equal to the proton synchrotron radiation, which dominates the GeV γ-ray emission. The results are within one order of magnitude of each other, suggesting that the hadronic synchrotron mirror model may provide a plausible explanation for the vHE γ-ray flare of 3C279.

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1. Introduction

Blazars are a class of radio-loud (jet-dominated) Active Galactic Nuclei (AGN) that are found in the centres of elliptical galaxies. There are two types: flat spectrum radio quasars (FSRQs), characterized by strong optical emission lines, and BL Lac objects, with weak or no emission lines in their optical spectra [Böttcher, 2007]. Most blazars are γ-ray loud due to relativistic jets pointed at a small angle with respect to our line of sight. Due to this, their emission is Doppler boosted, and radio interferometric observations reveal apparent superluminal motion [e.g., Kellermann et al., 2007]. The spectral energy distributions (SEDs) of blazars are characterized by two broad, non-thermal components. The low-frequency component is almost certainly caused by electron synchrotron emission. In leptonic models, the high-frequency component is caused by Compton scattering [Kusunose and Takahara, 2006, Böttcher, 2007]. However, alternatively this component can also be caused by hadronic processes [Mannheim and Biermann, 1992, Mannheim, 1993, Mücke et al., 2003], where the dominant γ-ray emission mechanisms are proton-synchrotron radiation and synchrotron emission from secondary particles produced on photo-pion-production interactions. Specifically, the relevant interactions are:

$$p+\gamma \rightarrow p+\pi^0 \rightarrow p+\gamma+\gamma \tag{1.1}$$

$$\text{or } \rightarrow n+\pi^+ \rightarrow n+\mu^+ +\nu_\mu \rightarrow n+e^+ +\nu_\mu+\nu_e+\nu_\mu \tag{1.2}$$

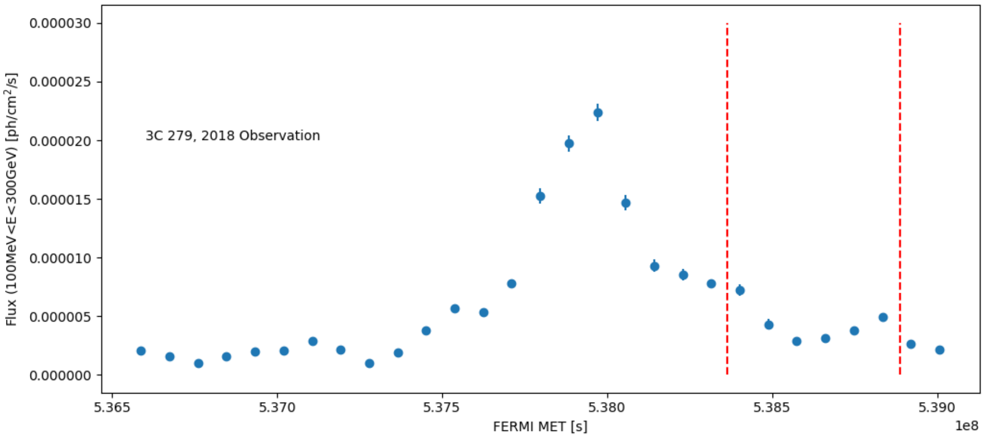

Figure 1: Fermi-LAT light-curve of GeV γ-rays, for the flare from 3C279 in January 2018, as per Atel #11239. H.E.S.S. target-of-opportunity observations were carried out during the period bounded by the vertical red lines. The second red line indicates the orphan flare detection. The delay between the Fermi LAT and the H.E.S.S. flares is 11 days.

Blazars show extreme variability across the electromagnetic spectrum. Some of these flares are accompanied by extremely fast variability of timescales down to a few minutes. In some cases, flaring events in one frequency band are not accompanied by flaring in other bands [Krawczynski et al., 2004]. Such events are termed orphan flares. Orphan flares are usually secondary flares following primary multi-wavelength flares, and are characterized by extreme variability and flaring in different bands. The causes of this variability and the conditions in and location of the high energy emission region are currently not well understood. Photo-pion production can only be efficient if the protons have a dense target photon field to interact with. Such target photon fields can either be the co-spatially produced electron-synchrotron radiation, or radiation fields from outside the jet [Mannheim and Biermann, 1992, Mannheim, 1993, Mücke et al., 2003].

Throughout this paper, physical quantities will be parameterized by $Q = 10^x Q_x$ in c.g.s. units.

2. 3C279 Flare

On the 28th of January, the High Energy Stereoscopic System (H.E.S.S. the world's largest ground-based gamma-ray observatory, located in Namibia) detected an orphan very-high-energy (VHE; $E > 100$ GeV) γ-ray flare from the FSRQ 3C279. 3C279 is a γ-ray loud FSRQ with a redshift of z = 0.538 [e.g., Marziani et al., 1996].

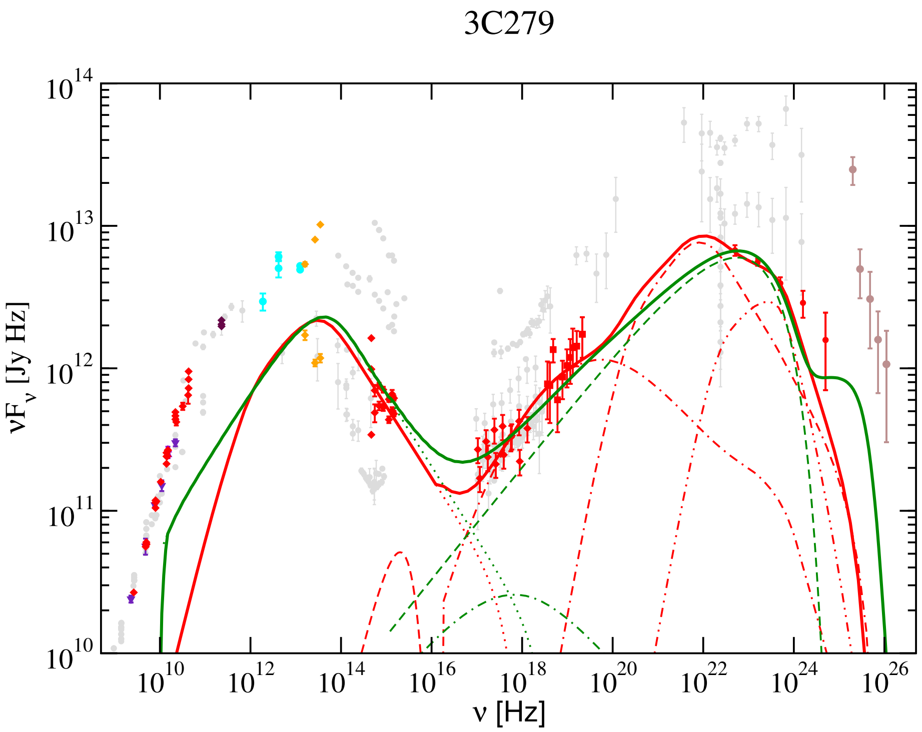

Figure 2: Spectral Energy Distribution (SED) of 3C279 with a lepto-hadronic model fit (green line), and a leptonic fit (red line) [from Böttcher et al., 2013]. The hadronic (green) model SED consists of three components: the low-energy component caused by electron-synchrotron radiation, the high-energy component caused by proton-synchrotron radiation, and a third very-high energy component caused by photo-pion interactions and subsequent electromagnetic cascades.

Figure 1 shows the Fermi-LAT γ-ray light-curve of 3C279 and the H.E.S.S. observation during the January 2018 flare. Orphan flares have to be caused by different processes than normal γ-ray flares, which are typically broad-band flares, characterized by variability across the entire electromagnetic spectrum.

Specifically, the Hadronic Synchrotron Mirror Model, originally proposed in [Böttcher, 2005] will be re-visited in this study, to see if it can provide a consistent explanation of the orphan flare from 3C279. A success of this model would indicate that protons are accelerated to ultra-relativistic energies in the jets of blazars, which might then also be associated with the production of very-high-energy neutrinos.

As shown in Figure 2, the lepto-hadronic model fit predicts a very-high-energy bump beyond the proton-synchrotron dominated γ-ray spectrum, due to photo-hadronic processes, which could be enhanced in a synchrotron-mirror scenario. This would lift the photo-pion production induced VHE component to the level of the proton-synchrotron component, producing an orphan VHE γ-ray flare. The aim of this paper is to investigate the feasibility of such a scenario through a first-principles, analytical estimate of the expected synchrotron-mirror photon density.

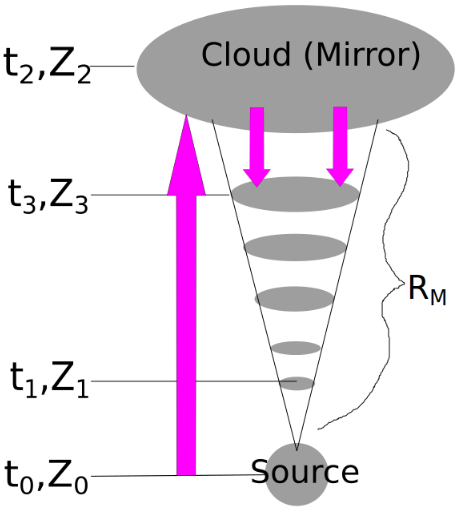

Figure 3: Sketch of the geometry of the model. As in [Böttcher, 2007], synchrotron emission is produced at time t_1 in an emission region propagating outward along the jet. At time t_2, the synchrotron emission is reflected by a cloud near the jet trajectory, which acts as a mirror. A secondary flare is then produced when the reflected synchrotron photons re-enter the emission region and encounter the still relativistic protons at time t_3.

3. The Synchrotron-Mirror Model

The goal of our analytical study of the hadronic synchrotron-mirror model is to determine if the target photon density from the synchrotron-mirror can plausibly be dense enough for proton-gamma interactions to produce a significant VHE γ-ray flare. The geometry is sketched in figure 3. The emission region moves at highly relativistic speeds $\beta_\Gamma \approx 1$ corresponding to bulk Lorentz factor $\Gamma = 10\Gamma_1 >> 1$. The emission is relativistically beamed at a small angle ($\theta \sim 1/\Gamma$) with respect to the jet axis, which, in the case of blazars like 3C279, is closely aligned with the observer's line of sight [e.g., Romero et al., 2017]. The orphan VHE flare was observed to be delayed by $\Delta t \equiv 11 t_{11}$ days, implying that the distance travelled by the emission region from the time of the primary gamma-ray flare to the location of the cloud is $R_m = 2\Gamma^2 c \Delta t = 5.7 \times 10^{18} \Gamma_1^2 t_{11}$ cm.

The electron-synchrotron emission from the blob hits is reflected off the cloud and re-enters the still relativistic emission region, constituting an intense target photon field for photo-pion production [Böttcher, 2005]. We assume that the emission region continues to produce optical – UV synchrotron radiation at the level of $\nu F_\nu(sy) \sim 10^{12}$ Jy Hz, as typically observed from 3C279, and a fraction τ of the synchrotron flux from the moving emission region is reprocessed quasi-isotropically by the cloud. Integrating the contributions from all points along the jet from the primary flare to the jet-cloud interaction (orphan flare), properly taking into account all light-travel-time effects, we find that the energy density of the reflected synchrotron radiation re-entering the emission region in the co-moving frame is given by:

$$\langle u'_{R,sy}(t_1)\rangle = \frac{4\Gamma^6 \nu F_\nu(sy) d_L^2 \tau R_{cl}^2}{3(R_m - R_b)} \int_0^{\frac{R_m-R_b}{\beta c}} \frac{dt_1}{(R_m - \beta c t_1)^2 (R_m - \frac{\beta c t_1}{2})^2} \tag{3.1}$$

where $R_b \equiv 10^{16} R_{b,16}$ cm is the radius of the blob which was estimated from the variability time scale through causality arguments, $R_{cl} \equiv 10^{17} R_{cl,17}$ cm is the radius of the cloud, d_L is the Luminosity distance, and $\tau \equiv 0.1\,\tau_{-1}$ is the reprocessing fraction of the cloud. The integral can be solved analytically to yield:

$$\langle u'_{R,sy}(t_1)\rangle = \frac{4\Gamma^6 \nu F_\nu(sy) d_L^2 \tau R_{cl}^2}{3(R_m - R_b)} \left(\frac{4}{(\beta c)^4} \left[\frac{1}{\alpha^2 x_f} + \frac{2}{\alpha^3} \left(\frac{t_f}{2x_f} \right) \right] \right) \tag{3.2}$$

where $t_f = \frac{R_m - R_b}{\beta c}$ is the total integration time, $\alpha = \frac{R_m}{\beta c}$ is the time it takes the blob to move to the center of the cloud and $x_f = \alpha - t_f$ is the time for the interaction to take place. Since $t_f \sim \alpha >> x_f$, the term $\frac{1}{\alpha^2 x_f}$ in the square brackets in Eq. (3.2) dominates the result. Neglecting the sub-dominant term, the target Photon density is:

$$\langle u'_{R,sy}(t_1)\rangle \approx 33\ \mathrm{t}_{11}^{-3} \tau_{-1} \mathrm{R}_{cl,17} \mathrm{R}_{b,16}^{-1}\ \mathrm{erg\,cm^{-3}} \tag{3.3}$$

Most remarkably, due to the scaling of the mirror distance in terms of the delay time, all explicit dependencies on the bulk Lorentz factor Γ cancel out in the result of Eq. (3.3), but a strong dependence on the delay time t_{11} remains.

4. Discussion

The target photon density from the synchrotron-mirror model estimated in the previous section (Eq. 3.3) now needs to be compared to the density required for proton-gamma interactions to produce a radiative output comparable to the proton-synchrotron dominated GeV γ-ray flux. This will be the case if the proton energy-loss rate due to photo-pion production on the synchrotron-mirror target photon field is comparable to the energy loss rate due to proton synchrotron emission. For proton synchrotron radiation in a magnetic field in units of Gauss (B_G) and a Doppler factor $\delta \equiv 10\,\delta_1 \approx \Gamma$, the photon energy density that leads to equal p-γ and proton synchrotron energy losses is

$$u'_{ph} \approx 380\ \mathrm{erg \cdot cm^{-3}}\ \mathrm{B}_G^{\frac{3}{2}}\ \delta_1^{\frac{1}{2}} \tag{4.1}$$

This is one order of magnitude larger than the result in 3.3 with the assumed default parameter values. In case of a larger cloud, $R_{cl} > 10^{17}\ cm$, a smaller emission region, or a larger reflective fraction τ of the cloud, it may be possible for pγ interactions on the synchrotron-mirror photons to make a significant contribution to the VHE γ-ray spectrum. Thus, based on our analytical estimate, the hadronic synchrotron mirror model may, in exceptional circumstances, produce orphan VHE γ-ray flares in blazars such as 3C279.

Clouds potentially acting as mirrors are found in the broad line region (BLR) where they may occasionally cross or, at least, closely approach the path of the jet. This may be put in the context of recent work by, e.g., Zacharias et al. [2017, 2019] who propose that such cloud-jet interactions may also be responsible for long-term blazar flares with quasi-symmetric light curves, as observed in the 4-month-long, extended flare state of CTA 102. Most notably, if such a hadronic synchrotron-mirror model is indeed at work in 3C279, it suggests the acceleration of high-energy Cosmic Rays in the jet of (at least) this blazar and associated production of very-high-energy neutrinos from pγ interactions.

On-going work on this project includes a numerical representation of this model and a comparison to alternative models for orphan γ-ray flares, such as the multizone or structured jet models.

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[1] Any opinion, finding and conclusion or recommendation expressed in this material is that of the authors and the NRF does not accept any liability in this regard.

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