A Hadronic Synchrotron Mirror Model for the “orphan” TeV flare in 1ES 1959+650

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ABSTRACT

Very-high-energy γ-ray flares of TeV blazars are generally accompanied by simultaneous flaring activity in X-rays. The recent observations by the Whipple collaboration of an “orphan” TeV flare of 1ES 1959+650 (without simultaneous X-ray flare) is very hard to reconcile with the standard leptonic SSC model which is routinely very successfully employed to explain the SED and spectral variability of TeV blazars. In this paper, an alternative scenario is suggested in which the “orphan” TeV flare may originate from relativistic protons, interacting with an external photon field supplied by electron-synchrotron radiation reflected off a dilute reflector. While the external photons will be virtually “invisible” to the co-moving ultrarelativistic electrons in the jet due to Klein-Nishina effects, their Doppler boosted energy is high enough to excite the ∆ resonance from relativistic protons with Lorentz factors of $\gamma_p \sim 10^3 – 10^4$. This model is capable of explaining the “orphan” TeV flare of 1ES 1959+650 with plausible parameters, thus constraining the number and characteristic energy of relativistic protons in the jet of this blazar.

Subject headings: galaxies: active — BL Lacertae objects: individual (1ES 1959+650) — gamma-rays: theory — radiation mechanisms: non-thermal

1. Introduction

Blazars are a peculiar class of active galactic nuclei, consisting of optically violently variable (OVV), gamma-ray loud quasars and BL Lac objects. They have been observed at all wavelengths, from radio through very-high energy (VHE) γ-rays. Six blazars (Mrk 421:

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Punch et al. (1992); Mrk 501: Quinn et al. (1996); PKS 2155-314: Chadwick et al. (1999); 1ES 2344+514: Catanese et al. (1998); 1H 1426+428: Horan et al. (2002); 1ES 1959+650: Kajino et al. (1999); Holder et al. (2003)) have now been detected at VHE $\gamma$-rays ($>350$ GeV) by ground-based air Čerenkov telescopes. Blazars exhibit variability at all wavelengths on various time scales. Radio interferometry often reveals one-sided kpc-scale jets with apparent superluminal motion. The high inferred isotropic luminosities, short variability time scales, and superluminal motion provide conclusive evidence that blazars are sources of relativistic jets pointing at a small angle with respect to our line of sight.

One of the key unresolved questions in the field of blazar research to date is the nature of relativistic particles in blazar jets. In the framework of relativistic jet models, the low-frequency (radio – optical/UV) emission from blazars is interpreted as synchrotron emission from nonthermal relativistic electrons in the jet. The high-frequency (X-ray – $\gamma$-ray) emission could either be produced via Compton upscattering of low frequency radiation by the same electrons responsible for the synchrotron emission (for a recent review see, e.g., Böttcher 2002), or due to hadronic processes initiated by relativistic protons co-accelerated with the electrons (for a recent discussion see, e.g. Mücke et al. 2003). The lack of knowledge of the primary jet launching mechanism and the difficulty in constraining the jet composition from general energetics considerations currently leave both leptonic and hadronic models open as viable possibilities. In many cases, both types of models can provide acceptable fits to the observed broadband spectral energy distributions (SEDs) of BL Lac objects, in particular the TeV blazars (see, e.g., Mastichiadis & Kirk (1997); Pian et al. (1998); Petry et al. (2000); Krawczynski, Coppi, & Aharonian (2002) for leptonic and Mücke et al. (2003) for hadronic models).

In the framework of leptonic jet models, TeV blazars are successfully modelled by SSC models in which the high-energy emission is produced by Compton scattering of electron-synchrotron radiation off the same ultrarelativistic electrons producing the synchrotron emission (e.g. Mastichiadis & Kirk 1997; Pian et al. 1998; Petry et al. 2000; Krawczynski, Coppi, & Aharonian 2002). Such models have been successful in modeling not only the SEDs, but also the detailed spectral variability, including spectral hysteresis at X-ray energies, of several TeV blazars (e.g., Kirk, Rieger, & Mastichiadis 1998; Georganopoulos & Marscher 1998; Kataoka et al. 2000; Kusunose, Takahara, & Li 2000; Li & Kusunose 2000). An inevitable prediction of the SSC model is that any flaring activity at TeV energies should be accompanied by a quasi-simultaneous flare in the synchrotron component. Even if the synchrotron flare does not necessarily have to be very pronounced at X-ray energies, since the TeV photons might be produced by Compton upscattering of seed photons that are observed predominantly in the radio – optical regime, there should always be a significant imprint of the TeV flare in the optical and X-ray light curves.
This prediction is in striking contrast to the recent observation of Krawczynski et al. (2004) of an “orphan” TeV flare seen in the Whipple light curve of the TeV blazar 1ES 1959+650 during a multiwavelength campaign in the late spring and summer of 2002. The object displayed first a quasi-simultaneous TeV and X-ray (RXTE) flare, followed by a well sampled, smooth decline of the X-ray flux over the following \( \sim 1 \) month. However, during this smooth decline, a second TeV flare, \( \sim 20 \) days after the initial one, was observed, which was only accompanied by very moderate \( \lesssim 0.1 \text{mag} \) flaring activity in the R and V bands. This behavior is clearly unexpected in a purely leptonic SSC blazar jet model.

In light of their great success to model both the broadband SEDs and spectral variability of TeV blazars in great detail, leptonic models might still be a very reasonable starting point for further investigations of this peculiar flaring behavior of 1ES 1959+650. However, even if one assumes that the high-energy emission is usually dominated by leptonic processes in blazar jets in general and in 1ES 1959+650 in particular, one would naturally expect that the emitting plasma in blazar jets is not a pure \( e^+e^- \) pair plasma, but contains a non-negligible admixture of protons. For example, based on X-ray luminosity constraints from observations, Sikora & Madejski (2000) find that even if \( e^+e^- \) pairs outnumber protons by a large margin (factor of \( \sim 50 \) ), blazar jets might still be dynamically dominated by their baryon content. Similar conclusions have been reached by Kino & Takahara (2004), ruling out a pure electron-proton plasma in energy equilibrium between electrons and protons or a pure electron-positron pair plasma. These conclusions are also supported by energy requirements in large-scale extragalactic X-ray jets observed by Chandra which seem to remain relativistic out to kpc and even Mpc distances from the central engine (see, e.g. Ghisellini & Celotti 2001; Sambruna 2003)).

Detailed simulations of particle acceleration at relativistic shocks or shear layers show that a wide variety of particle spectra may result in such scenarios (e.g., Ostrowski & Bednarz 2002; Stawarz & Ostrowski 2003; Ellison & Double 2004), greatly differing from the standard spectral index of 2.2 – 2.3 previously believed to be a universal value in relativistic shock acceleration (e.g., Gallant, Achterberg, & Kirk 1999; Achterberg et al. 2001). Thus, both the nature of the matter in blazar jets and the energy spectra of ultrarelativistic particles injected into the emission regions in blazar jets are difficult to constrain from first principles. Consequently, also their kinetic luminosity is hard to constrain. However, if Fermi acceleration plays a major role in the energization of electrons (pairs) in leptonic jets, then one would naturally expect that also protons are accelerated to relativistic energies, though conceivably not exceeding the energy threshold to boost the bulk of the available soft photons up to the energy of the \( \Delta \) resonance at 1232 MeV in the proton’s rest frame to initiate pion production processes. While the size-scale constraint would allow the acceleration of protons up to Lorentz factors of \( \gamma_{p,\text{max}} \sim 3 \times 10^8 B_{-1} R_{16} \) (where \( B = 0.1 \) \( B_{-1} \) G is the co-moving
magnetic field and $R = 10^{16} R_{16}$ cm is the size of the emitting region), factors related to, e.g., the incomplete development of plasma wave turbulences and superluminal magnetic-field configurations at oblique shocks (Ostrowski & Bednarz 2002; Ellison & Double 2004) may severely limit the maximum energies of protons by several orders of magnitude.

It has previously been suggested (e.g., Atoyan & Dermer 2003) that the presence of external photon fields may substantially lower the effective proton energy threshold for $p\gamma$ pion production compared to the standard hadronic-jet scenario based on synchrotron target photons. They have also pointed out that the conversion of protons to neutrons via charged pion production ($p\gamma \rightarrow n\pi^+$) may facilitate the transport of kinetic energy in baryons out to kpc scales. For $\gamma_{p,\text{max}} = 10^4 \gamma_4$, photon energies of $E'_\text{ph} \sim E_\Delta/\gamma_{p,\text{max}} \sim 30 \gamma_4^{-1}$ keV in the co-moving frame of the emission region would be required in order to initiate $p\gamma$ processes. Such photon energies are unlikely to be achieved by intrinsic (electron synchrotron) photons, but they may occasionally be provided by external photon sources due to the Doppler blue shift into the emission region. For example, quasi-isotropic radiation fields from re-processed accretion-disk photons (Sikora, Begelman, & Rees 1994; Dermer, Sturner, & Schlickeiser 1997) or reflected jet synchrotron emission (Ghisellini & Madau 1996; Böttcher & Dermer 1998) are good candidates for external soft photon sources to occasionally exceed the $p\gamma$ pion production threshold for relativistic protons of $\gamma'_p \sim 10^3 - 10^4$.

This paper presents a discussion of the idea that the “orphan” TeV flare in 1ES 1959+650 resulted from $\pi^0$ decay following $\gamma p$ pion production on an external photon field dominated by photons from the first, simultaneous synchrotron + TeV flare.

In §2, the basic model geometry and parameter choices, guided by the observations of 1ES 1959+650, are outlined. Analytic estimates constraining model parameters, in particular the hadron number density and energy content in the jet are presented in §3. §4 contains a summary and brief discussion.

2. Model setup and parameter estimates

The basic model geometry is sketched in Fig. 1. A blob filled with ultrarelativistic electrons and relativistic protons is traveling along the relativistic jet, defining the positive $z$ axis. Particles are accelerated very close to the central engine (F1) in an explosive event which is producing the initial synchrotron + TeV flare via the leptonic SSC mechanism. Synchrotron emission from this flare is reflected off a gas cloud (the mirror M) located at a distance $R_m$ from the central engine. The cloud has a reprocessing optical depth $\tau_m = 10^{-1} \tau_{-1}$ and a radius $R_c = 10^{17} R_{c,17}$ cm, implying an average density of $n_c = 10^6 n_{6} \text{ cm}^{-3}$.
with $n_6 \sim 1.5$.

The characteristic synchrotron photon energy during the primary flare of 1ES 1959+650 was $E'_{\text{sy}} \sim 1 \Gamma^{-1} E_{\text{sy},1}$ keV in the co-moving frame, implying a characteristic photon energy of the reflected synchrotron radiation of $E'_{\text{Resy}} \sim 100 \Gamma_1 E_{\text{sy},1}$ keV, where $\Gamma = 10 \Gamma_1$ is the bulk Lorentz factor of the emission region, and it is assumed that the Doppler boosting factor $D \approx \Gamma$. Here, the observed peak of the synchrotron spectrum has been parametrized as $E_{\text{sy}} = 10 E_{\text{sy},1}$ keV. Relativistic electrons with $\gamma'_e \gtrsim 10$ will be very inefficient in Compton upscattering this radiation field due to the rapid decline of the Klein-Nishina cross section.

Here and in the remainder of this paper, quantities in the frame of the emission region ("blob") are denoted by primed symbols, while unprimed symbols refer to quantities in the stationary system of the AGN. Considering VHE photon production from the decay of neutral pions with co-moving Lorentz factors $\gamma'_{\pi^0}$, we may assume that $\gamma'_{\pi^0} \approx \gamma'_{\Delta} \approx \gamma'_{p}$. The observable spectrum of $\pi^0$ decay photons will then extend out to $E_{\pi^0 \rightarrow 2\gamma} \sim 7 \gamma_4 \Gamma_1$ TeV.

The observed time delay between the primary synchrotron flare and the secondary flare due to interactions of the blob with the first reflected synchrotron flare photons to arrive back at the blob was $\Delta t_{\text{obs}} = 20 \Delta t_{20}$ days, and is related to the distance of the reflector by

$$\Delta t_{\text{obs}} \approx \frac{R_m}{2 \Gamma^2 c}.$$  

Thus, $R_m \approx 3 \Gamma_4^2 \Delta t_{20}$ pc. A cloud of reflecting gas with the characteristics specified above, at this distance from a central source of the ionizing continuum radiation from a central accretion disk with luminosity $L_D = 10^{44} L_{44}$ ergs s$^{-1}$ will remain largely neutral (ionization parameter $\xi = L_D/(4\pi R_m^2 n_c) \sim 8 \times 10^{-2} L_{44} (R_m/3\text{pc})^{-2} n_6^{-1}$). Its optical emission line luminosity will be limited by $L_{\text{line}} < L_D (R_c/R_m)^2 = 10^{40} L_{44} R_{c,17}^2 (R_m/3\text{pc})^{-2}$ ergs s$^{-1}$, corresponding to a line flux of $F_{\text{line}} < 2 \times 10^{-15} L_{44} R_{c,17}^2 (R_m/3\text{pc})^{-2}$ ergs cm$^{-2}$ s$^{-1}$ which is negligible compared to the jet synchrotron continuum, consistent with the classification of 1ES 1959+650 as a BL Lac object.

The duration of the flare, $w_{\text{fl}}^{\text{obs}}$ will then be determined by the time it takes for the blob to travel from the location $z_0$ of the onset of the secondary flare to the mirror at $R_m$:

$$w_{\text{fl}}^{\text{obs}} = \frac{(R_m - z_0)(1 - \beta)}{\beta c} \approx R_m/8 \Gamma_4 c \approx 1.2 \Gamma_1^{-2} \text{ hr},$$  

where $\beta c = \sqrt{1 - 1/\Gamma^2} c$ is the speed of the blob which is assumed to remain constant throughout the period considered here. From the observed $\nu F_\nu$ fluxes of the primary synchrotron flare and the secondary TeV flare, $\nu F_\nu(\text{sy}) \sim 5 \times 10^{-10}$ ergs s$^{-1}$ cm$^{-2}$ and
\( \nu F_{\nu}(600 \text{ GeV}) \sim 3 \times 10^{-10} \text{ ergs s}^{-1} \text{ cm}^{-2} \) (see Fig. 2 and Krawczynski et al. 2004), we find the co-moving luminosities, \( L_{\text{sy}}' \sim 2.5 \times 10^{41} \Gamma_1^{-4} \text{ ergs s}^{-1} \) and \( L_{\text{VHE}}' \sim 1.5 \times 10^{41} \Gamma_1^{-4} \text{ ergs s}^{-1} \). Here, an \( \Omega_\Lambda = 0.7, \Omega_\text{m} = 0.3 \) cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) was used. With these parameters, 1ES 1959+650 with \( z = 0.047 \) is located at a luminosity distance of \( d_L = 210 \text{ Mpc} \). If the reflecting cloud is located in a direction close to our line of sight, the energy density of jet synchrotron photons impinging onto the mirror is

\[
u F_{\nu}(\text{sy}) \sim \frac{d^2}{R_m^2} \nu F_{\nu}(\text{sy}) \sim 1.3 \times 10^{51} \Gamma_1^{-4} \Delta t_{20}^{-2} \text{ ergs cm}^{-3}. \] (3)

The reflected synchrotron flux will be received by the blob very close to (and within) the mirror, so that its photon energy density, in the co-moving frame of the blob, is given by

\[
u F_{\nu}(\text{sy}) \sim \frac{\tau_m \Gamma^2 u_{\text{sy}}(R_m)}{4\pi} \sim 1.0 \times 10^{51} \Gamma_1^{-2} \Delta t_{20}^{-2} \tau \text{ ergs cm}^{-3}. \] (4)

This reflected synchrotron photon field can now be used to estimate the energy and density of relativistic protons needed in the jet to produce the “orphan” TeV flare in 1ES 1959+650 via \( \gamma p \) pion production and subsequent \( \pi^0 \) decay, and to estimate the expected signatures of such a scenario at lower (optical – X-ray) frequencies.

### 3. Results

The co-moving luminosity from \( p\gamma \rightarrow \Delta \rightarrow p + \pi^0 \rightarrow p + 2\gamma \) produced by protons of a given energy \( \gamma'_{p} \) is given by

\[
u F_{\nu}(\text{VHE}) \sim \frac{8}{3} c \sigma_{\Delta} u_{\text{Ry}} \gamma'_{p} \frac{70 \text{ MeV}}{E'_{\text{Ry}}} N_p(\gamma'_{p}). \] (5)

where \( \sigma_{\Delta} \approx 300 \mu \text{b} \) is the \( \Delta \) resonance cross section and \( N_p(\gamma'_{p}) \) is the number of protons at energy \( \gamma'_{p} \approx (300 \text{ MeV})/E'_{\text{Ry}} \approx 3 \times 10^3 \Gamma_1^{-1} E_{\text{sy},1}^{-1} \). With this, the observable \( \nu F_{\nu} \) peak flux in the TeV flare can be estimated as

\[
u F_{\nu}(\text{VHE}) \sim \frac{L'_{\text{VHE}} \Gamma^4}{4\pi d_L^2} \sim 1.0 \times 10^{-56} N_p(\gamma'_{p}) \Delta t_{20}^{-2} \tau \text{ ergs cm}^{-2} \text{ s}^{-1}. \] (6)

Setting this equal to the observed VHE peak flux yields

\[
u F_{\nu}(\text{VHE}) \sim \frac{L'_{\text{VHE}} \Gamma^4}{4\pi d_L^2} \sim 1.0 \times 10^{-56} N_p(\gamma'_{p}) \Delta t_{20}^{-2} \tau \text{ ergs cm}^{-2} \text{ s}^{-1}. \] (7)

\[
u F_{\nu}(\text{VHE}) \sim \frac{L'_{\text{VHE}} \Gamma^4}{4\pi d_L^2} \sim 1.0 \times 10^{-56} N_p(\gamma'_{p}) \Delta t_{20}^{-2} \tau \text{ ergs cm}^{-2} \text{ s}^{-1}. \] (6)
The spectrum of non-thermal protons in the blob may be expected to have a low-energy cut-off at relativistic energies. For example, if the non-thermal protons are injected into the jet as pickup ions from a relativistic shock wave traveling along the jet (see, e.g. Pohl & Schlickeiser 2000), this low-energy cutoff is expected at $\gamma_{p,\text{min}} \sim \Gamma = 10 \Gamma_1$. Assuming that the relativistic proton spectrum is a straight power-law with index $s$, the estimate (7) corresponds to a total relativistic proton number of

$$N_p \sim \frac{(3,000)^{1+s} \cdot 10^{14-s}}{s-1} \Gamma_1^{1-2s} \Delta t_2^2 \tau_{-1}^{-1} E_{sy,1}^{2-s}.$$ (8)

For a typical index $s = 2$, this corresponds to $N_p \sim 2.7 \cdot 10^{52} \Gamma_1^{-3} \Delta t_2^2 \tau_{-1}^{-1}$ and a relativistic proton number density of

$$n'_p \sim 6.4 \times 10^3 \Gamma_1^{-3} \Delta t_2^2 \tau_{-1}^{-1} R_{16}^{-3} \text{ cm}^{-3}.$$ (9)

Note the strong dependence on the bulk Lorentz factor. With values of $\Gamma_1 \sim 2$, the required proton density can be substantially less than the typical electron densities found in spectral modeling of blazars ($n'_e \sim 10^3 \text{ cm}^{-3}$), which is perfectly consistent with the pair/proton number density ratios inferred by Sikora & Madejski (2000). With $s = 2$ and a maximum Lorentz factor of relativistic protons of $\gamma_{p,\text{max}} \sim 10^4$, the total co-moving kinetic energy in relativistic protons in the blob is then

$$E'_{b,p} \sim 2.8 \times 10^{51} \Gamma_1^{-2} \Delta t_2^2 \tau_{-1}^{-1} \text{ erg}.$$ (10)

The kinetic luminosity carried by relativistic protons in the jet can then be estimated as

$$L_{p}^{\text{kin}} \sim 7.3 \times 10^{44} R_{16}^{-1} \Delta t_2^2 \tau_{-1}^{-1} f^{-3} \text{ ergs s}^{-1}$$ (11)

where $f = 10^{-3} f_{-3}$ is a filling factor accounting for the likely case that the relativistic proton plasma is concentrated only in individual blobs along the jet rather than being continuously distributed throughout the jet.

The radiative output from the $\Delta^+$ decay channel $p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+$, followed by $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$ will primarily consist of positron synchrotron radiation. Considering the kinematics of the pion and muon decay processes, one finds that the positron will carry away $\sim 1/3$ of the total pion energy. Consequently, we have $\gamma_{e^+} \sim (1/3) (m_\pi/m_e) \gamma'_p \sim 2.1 \times 10^5 \Gamma_1^{-1} E_{sy,1}^{-1}$. The synchrotron emission from the secondary positrons will peak at

$$E_{\text{sy},e^+} \sim 500 B_{-1} E_{sy,1}^{-2} \text{ eV},$$ (12)
i.e. typically in the UV or soft X-ray regime. Note that unlike the case of a proton blazar (with higher magnetic fields and much higher proton and positron Lorentz factors), the charged-pion decay channel will not initiate an electromagnetic cascade.

An estimate of the expected $\nu F_\nu$ flux in the $e^+$ synchrotron emission can be found in the following way. First of all, considering the co-moving dynamical time scale, $t'_\text{dyn} \sim R/c \sim 3.3 \times 10^5 R_{16} \text{ s}$ and the synchrotron cooling time scale,

$$t'_e \sim 3.7 \times 10^5 \Gamma_1 B_{-1}^{-2} E_{\text{sy},1} \text{ s},$$

we find that those are comparable, implying that the secondary positrons might lose a substantial fraction of their kinetic energy to radiation before potentially leaking out of the emission region. Second, we realize that the synchrotron cooling time scale will set the natural duration of the secondary $e^+$ synchrotron flare, which will be (in the observer’s frame)

$$\nu F_\nu \sim 3.7 \times 10^4 B_{-1}^{-2} E_{\text{sy},1} \text{ s}.$$  

Consequently, the duration of the $\pi^0$ decay VHE $\gamma$-ray flare is a factor of $f_w \equiv w_{\pi^0}^\text{obs} / w_{e^+}^\text{obs} \sim 0.12 B_{-2}^2 E_{\text{sy},1} \Gamma_1^{-2}$ shorter than the secondary synchrotron flare, so the observed $\nu F_\nu$ peak flux of the $e^+$ synchrotron flare should have been a factor of $f_w/3 \sim 0.04$ lower than that of the $\pi^0$ decay flare (note that 2/3 of the $\pi^+$ energy will go into neutrino emission), which yields

$$\nu F_{e^+sy}^\nu \sim 1.2 \times 10^{-11} \Gamma_1^{-2} B_{-1}^2 E_{\text{sy},1} \text{ ergs cm}^{-2} \text{ s}^{-1}$$

if the observed secondary VHE flare was due to $\pi^0$ decay photons. The expected $e^+$ synchrotron peak flux would thus have been only a few % of the observed RXTE $\nu F_\nu$ flux level during the secondary VHE flare, and have peaked at energies well below the RXTE energy range, leaving no observable trace in the X-ray light curve of the 1ES 1959+650 campaign of 2002. The expected level and spectral shape of the secondary $e^+$ synchrotron emission is represented by the dot-dashed line in Fig. 2.

An estimate of a possible optical flare can be obtained by realizing that positrons emitting synchrotron radiation in the optical regime are expected to be slow-cooling and thus basically reproduce the spectrum of the primary relativistic protons ($\sim \gamma^{-2}$), resulting in a synchrotron spectrum $\nu F_\nu \propto \nu^{1/2}$, which yields an R band flux from the secondary positron synchrotron emission of

$$\nu F_{e^+sy}^\nu (R) \sim 7.0 \times 10^{-13} \Gamma_1^{-1.5} B_{-1}^{1.5} E_{\text{sy},1}^2 \text{ ergs cm}^{-2} \text{ s}^{-1}.$$  

Comparing this to the average R-band flux around the time of the secondary (“orphan”) TeV flare, results in a predicted optical flare of

$$\Delta m \sim 0.05 \text{ mag},$$

(16)
which is perfectly consistent with the observed very small optical activity of $\Delta m_{\text{obs}} \lesssim 0.1^{\text{mag}}$ of 1ES 1959+650 at that time (Krawczynski et al. 2004).

4. Summary and Discussion

In this paper, I have suggested a model to explain the “orphan” TeV flare of 1ES 1959+650 in 2002, which followed a correlated X-ray + TeV flare by about 20 days. In this model, the secondary TeV flare resulted from $\pi^0$ decay following $p\gamma$ pion production by relativistic protons ($\gamma_p \sim 10^3 - 10^4$) on the primary synchrotron flare photons, reflected off a mirror cloud at a distance of a few pc from the central engine. Using the observational data from the 1ES 1959+650 observations in 2002, I have estimated the required parameters pertaining to the relativistic proton population in the jet in order to produce the secondary TeV flare with this mechanism. The main results of this investigation are:

- The required model setup is consistent with the BL Lac classification of 1ES 1959+650.
- The required density of relativistic protons in the jet is very well consistent with earlier findings that blazar jets might be dynamically dominated by the kinetic energy of relativistic protons, even if they are by far outnumbered by electron/positron pairs, which may dominate the radiative output of 1ES 1959+650 most of the time.
- The secondary $e^+$ synchrotron emission resulting from $\pi^+$ decay in this scenario is too weak and peaks at too low energies to leave an observable imprint in the RXTE light curve at the time of the secondary TeV flare, consistent with its non-detection (and, thus, with the appearance of the TeV flare as an “orphan” flare).
- The optical flare produced by secondary $e^+$ synchrotron emission is expected to produce only a very mild bump of $\Delta m \sim 0.05^{\text{mag}}$ in the R and V bands, which is perfectly consistent with the very moderate activity of the source during the secondary TeV flare.

A detailed investigation of the spectral and light curve features resulting in this scenario is currently underway and will be published in a forthcoming paper (Postnikov & Böttcher 2004, in preparation). This will also include the characteristics of the expected neutrino emission resulting from $\pi^+$ decay.

Another signature of relativistic protons in the framework of the model suggested here might arise from photo-pair production, $p\gamma \rightarrow pe^+e^-$. The threshold proton energy for this
process, in our parametrization is $\gamma_{\text{thr.pair}} \sim 5 \Gamma^{-1} E_{\text{sy,1}}^{-1}$. The bulk of pairs injected into the emission region from this process would thus have only mildly relativistic energies and would not leave significant non-thermal radiation signatures. However, it has been demonstrated by Kazanas & Mastichiadis (1999) (see also Kazanas, Georganopoulos & Mastichiadis 2002, 2004, for the application of this process to gamma-ray bursts) that the photo-pair production process can exceed a critical threshold beyond which a pair avalanche on synchrotron radiation of secondary pairs develops. The threshold proton energy to initiate such an avalanche has been evaluated by Kazanas & Mastichiadis (1999) to be $\gamma_{p,\text{crit}} \sim 10^4 B_{1}^{-1/3} \Gamma_{1}^{-2/3}$. Thus, if the emitting volume contains protons with energies $\gamma_p \gg 10^4$, this supercritical pair avalanche can lead to a strong synchrotron signal, extending far into the X-ray regime, which would naturally be expected to produce a corresponding SSC signature at $\gamma$-ray energies. Because of the strong synchrotron component of this scenario, these signatures are easily distinguishable. It is very well conceivable that the "supercritical pile" scenario (Kazanas & Mastichiadis 1999), indicative of protons with Lorentz factors of $\gamma_p \gg 10^4$, is responsible for simultaneous X-ray + TeV $\gamma$-ray flares, while the pion production scenario discussed here, indicative of protons with Lorentz factors of $10^3 \lesssim \gamma_p \lesssim 10^4$ produces orphan TeV flares. Protons with yet lower Lorentz factors may ultimately be probed by the radiation signatures of mildly relativistic or even thermal pairs injected through the $p\gamma$ pair production process of protons near threshold.

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Fig. 1.— Geometry of the model. A primary synchrotron flare is produced by the emission region (blob) near the center of the system (F1). Synchrotron emission is reflected at the mirror (M), and re-enters the blob at point F2, resulting in the secondary, “orphan” TeV flare due to $p\gamma$ pion production and subsequent $\pi^0$ decay.
Fig. 2.— Broadband spectral energy distribution of 1ES 1959+650. Filled symbols and the solid X-ray spectrum refer to the TeV high state, representative of the primary TeV flare; open symbols and the dotted X-ray spectrum refer to the low TeV state. The dot-dashed power-law indicates the predicted secondary $e^+$ synchrotron emission following $\pi^+$ decay. Data from Krawczynski et al. (2004).