Hadronic Correlated Flares from Mrk 501

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Abstract. We discuss the possibility of explaining the extraordinary, correlated X-ray/TeV flares observed during April 1997 from Mrk 501, by synchrotron-pair cascades injected by synchrotron radiation from ultra-high energy protons and muons. Evaluating the jet conditions required to explain the observed features of the flares, the allowed region for this model in the parameter space of jet magnetic field and Doppler factor is identified, and compared with the parameter choices of other, both hadronic and leptonic models presented in the literature. The present model requires magnetic fields similar to other hadronic models for gamma-ray blazars ($B > 30 \text{ G}$), but a lower Doppler factor ($D \lesssim 3$).

I CORRELATED FLARES AND THEIR EXPLANATION

In April 1997 the Beppo-SAX team observed X-ray flares from Mrk 501 [1], which are extraordinary in at least two respects: (a) they extend to energies beyond $200 \text{ keV}$, and (b) they show an extremely flat spectrum, in one case with a power law flux index $\gamma = 0.5$. Simultaneously, the Whipple and HEGRA Cherenkov telescopes observed correlated flares in the TeV band [2]. Integrating over a larger time window, both found that the high energy emission during this period has extended on average up to at least $20 \text{ TeV}$ [3], but with a significant curvature consistent with an exponential cutoff at $5 \text{ TeV}$. The most common way to explain this emission is the synchrotron-self Compton (SSC) model, which naturally expects correlated variability because both the X-ray and the TeV component are radiated by the same population of particles (electrons). Another appealing possibility seems, to explain the high energy emission as synchrotron radiation from ultra-high energy (UHE) protons, while the X-rays are produced by co-accelerated electrons [4,5]. However, both models share the problem to explain the hard X-ray spectral index, which requires an electron injection spectrum $dN_e / dE = 1 / E^n$ [1] (this is because synchrotron cooling steepens the stationary electron spectrum by one power compared to the injection spectrum). However, the Fermi shock acceleration mechanism, commonly assumed to energize the particles in the jets, cannot produce such hard spectra (the limit is $dN_e / dE = 1 / E^{1.5}$ [6]), and convincing alternatives for electron acceleration to TeV energies in jets have not been suggested jet.

It has been pointed out previously [7] that correlated variability can also find a natural explanation by considering the TeV and X-ray emission as different generations of a synchrotron-pair cascade, injected by UHE protons. This is a modification and extension of the proton-induced cascade (PIC) models [8], considering the synchrotron emission
of UHE protons and muons additionally to UHE gamma-ray injection by $^{0}$-decay. The $p=\text{synchrotron}$ component leads here to “narrow” cascades with an extremely flat spectrum, which peak in the TeV and X-ray regime. It has been shown that the asymptotic spectral indices predicted by this model for the X-ray and TeV cascade generations fit quite well to the indices measured by Beppo-SAX and HEGRA/Whipple, respectively [7], and this for particle injection spectra which are canonically expected from Fermi acceleration. In contrast to pure proton-synchrotron and SSC models this model assumes that the jet is moderately optically thick at TeV energies, to allow for a reprocessing of the power into the X-ray regime. In the following we shall derive the allowed region in the jet-parameter space to explain the observed photon energies in the April 1997 flares from Mrk 501 within this scenario, and compare with the parameter choice of other models. A detailed fit to the flare spectra, employing the full set of particle and photon transport equations will be presented elsewhere (Rachen & Mannheim, in preparation).

II CONDITIONS FOR TEV/X-RAY CASCADES

Mücke & Protheroe [4] have argued that the idea of reprocessing TeV photons in a cascade to X-ray energies is incompatible with a dominant production of TeV photons by proton-synchrotron radiation. This is because synchrotron radiation from protons accelerated on their Larmor time scale, which is the fastest possible for Fermi acceleration, has a high energy limit at $\gamma_{\text{syn},p} \geq \frac{3m_p c^2 D}{F}$, where $D$ is the jet Doppler factor and $F$ the fine structure constant. The condition $\gamma_{\text{syn},p} > 5\text{TeV}$ then requires $D > 12$, which implies for the observed luminosity from Mrk 501 that the jet is optically thin for TeV photons. The requirement on the jet Doppler factor can be relaxed, however, if we consider synchrotron radiation from photohadronically produced muons [10], for which $\gamma_{\text{syn},\mu} = (\frac{m_\mu}{m_p})^{\gamma_{\text{syn},p}}$. More precisely, the condition for explaining the observed multi-TeV emission by muon synchrotron radiation is

$$\gamma_{\text{syn},\mu} \geq \frac{3}{8} \frac{m_e^2 c^2 B}{m_p} \frac{\gamma_{p}^2 D}{B_c} > 5\text{TeV} ;$$

where $B_c = 4 \times 10^{3} \text{G}$ is the critical magnetic field, $B$ is the jet magnetic field, and $\gamma_p$ is the maximum proton Lorentz factor, which is given as a function of $B$ and $D$ depending on the dominant cooling process (see Ref. [10] for details). Similarly, we can write the condition $\gamma_{\text{syn},\mu} \geq (3^{\gamma_p} (B = m_e c^2 B c D )^{\gamma_{\text{syn},p}}) > 200 \text{keV}$ for the requirement that the next photon generation in the synchrotron-pair cascade explains the observed X-ray photon energies. Two more conditions arise from the assumption that muon synchrotron radiation is relevant at all, compared to proton synchrotron radiation: (a) the time scale for photoproduction of mesons must be at least comparable

1) Despite occasional, contrary claims in the literature this is not in conflict with observations, since in a homogeneous emitter absorption only induces a steepening of the power-law spectrum by the target photon index $\gamma$, rather than an exponential cutoff [9,7]. The reader may keep this in mind when comparing the jet Doppler factors derived here with common “lower limits”, which all assume that the jet emission is optically thin for all observed energies.
with the synchrotron loss time of the protons \( t_p < t_{p,\text{syn}} \); (b) muons can lose a significant fraction of their energy before they decay \( t_{\mu,\text{syn}} < t_p \). Both conditions have been evaluated following Rachen & Mészáros [10], where we assume a spherical emission region of radius \( R = 10^{15} \text{ cm} \) with an observed (isotropic) luminosity of \( 10^{42} \text{ erg s}^{-1} \) at \( 10^{12} \text{ Hz} \) and a soft photon spectrum extending up to \( 1 \text{ keV} \) following \( dN_{\gamma \gamma} = \frac{d}{1.85} \). This target photon spectrum is theoretically motivated and does not match the observed infrared-to-X-ray spectrum from Mrk 501, which probably arises from a much larger emission volume since it is not strongly variable, and hence does not necessarily dominate the local photon density in the much smaller, variable emission region. At last, we have to consider the opacity for absorption, where we define the opacity-break energy by
and require $0 \text{ TeV} < E < 1 \text{ TeV}$, to ensure both sufficient emission of TeV radiation and sufficient cascade reprocessing to produce the X-ray flare.

III DISCUSSION AND COMPARISON WITH OTHER MODELS

Fig. 1 shows the conditions discussed above as limiting lines in the parameter space of jet magnetic field $B$ and Doppler factor $D$. We see that the condition $t_p < t_{p,p\beta \gamma}$, together with Eqs. (1) and (2) define a small allowed region in the parameter space, close to the “star-point” of equal cooling times defined by Rachen & Mészáros [10]. Other conditions turn out to be less restrictive for the present case. The result of Mücke & Protheroe [4], who also considered muon-synchrotron radiation and cascade reprocessing in their MC simulations and found both effects insignificant, can thus be understood by their parameter choice (marked as point $<A>$ in Fig. 1), which implied $t_{p,p\beta \gamma} > 10 \text{ TeV}$. We note that the jet Doppler factor determined here ($D > 3$) is significantly lower than those assumed in both pure proton-synchrotron and SSC models.

The small allowed parameter region would also explain why flares like those seen in April 1997 are rather rare events. We emphasize that explaining TeV radiation alone by hadronic phenomena, like PIC or proton-synchrotron radiation, is possible for a much larger set of parameters. Also correlated variability may arise from less restrictive settings, for example by correlated acceleration of protons and electrons in the jet [4]. Finally, the fact that the different models are so clearly separated in the parameter space opens the chance to distinguish between them by determining the jet Doppler factor and magnetic field independent of the assumed radiative mechanism.

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