Abstract. Proton acceleration in nearby blazars can be diagnosed measuring their intense TeV γ-ray emission. Flux predictions for 1101+384 (Mrk421) and 1219+285 (ON231), both strong EGRET sources (0.1−10 GeV), are obtained from model spectra of unsaturated synchrotron pair cascades fitted to publicly available multifrequency data. An experimental effort to confirm the predicted emission in the range 1-10 TeV would be of great importance for the problems of the origin of cosmic rays, the era of galaxy formation and the cosmological distance scale.

1. Introduction

1.1. Relativistic Jets

It came as a big surprise to most of the community when numerous powerful extragalactic γ-ray sources were discovered with the Energetic Gamma Ray Experiment Telescope EGRET onboard the Compton Gamma-Ray Observatory CGRO (Fichtel et al. 1994, von Montigny et al. 1994). The sources were soon identified as blazars, a subclass of active galactic nuclei (AGN), which are known to be the most powerful and rapidly variable nonthermal emitters also in other energy bands (Bregman 1990). The most intriguing fact about the discovery was that the received energy flux from many of these enigmatic objects is dominated by γ-rays. The precursor experiment COS-B had already indicated the existence of such γ-ray dominated extragalactic sources, baptized ‘proton quasars’ by Moffat et al. (1983). The TeV detection of Mrk421 by the Whipple group makes it probable that the blazar γ-ray spectra extend to still higher energies. Although it is already difficult to conceive that γ-ray sources as powerful as Mrk421 with \( L_\gamma \approx 10^{43} \text{ erg s}^{-1} \) exist in nature, some blazars detected by EGRET had apparent γ-ray luminosities of even \( L_\gamma \approx 10^{48} \text{ erg s}^{-1} \).

These new challenging observations can be explained assuming that the γ-rays are emitted in a lighthouse beam directed towards the observer (McBreen 1979). The beaming pattern, and thus the blazar phenomenon, arises from the relativistic bulk motion of plasma jets ejected from the vicinity of a supermassive black hole (Blandford & Königl 1979). Relativistic radio jets are commonly observed in flat-spectrum radio sources and superluminal expansion of the radio structure indicates bulk motion with Lorentz factors \( \gamma_j = 10 – 100 \) (Begelman et al. 1994). Whereas most particles in the jet plasma remain in thermal equilibrium, a small fraction of them is accelerated to high energies retaining isotropy in the comoving frame by pitch-angle scattering. Most probably, particles gain energy by repeatedly crossing collisionless shock fronts in the supersonic jet flow (Drury 1983, Begelman & Kirk 1990). A power law energy distribution indicates the stochastic nature of the acceleration mechanism.
1.2. The radiation process responsible for $\gamma$-ray emission

The high particle energies and the twenty orders of magnitude in frequency of the emitted nonthermal radiation are reminiscent of the properties of cosmic rays in our own Galaxy where electrons produce synchrotron radio emission and protons with Lorentz factors up to $10^{11}$ generate energetic $\gamma$-rays by pion production $p + p \rightarrow \pi^0 + X$ and their subsequent decay. Proton-matter interactions can not be the radiation mechanism responsible for the variable and highly luminous $\gamma$-ray emission from blazars, since this would require unrealistically large amounts of target matter in the jets. It would also imply a significant enhancement of light-elements due to spallation of heavier nuclei which has not been observed (Baldwin et al. 1979). However, it was noticed by Blumenthal (1970) and Colgate (1983) that the compact radiation fields in extragalactic radio sources represent by far the most important target for relativistic protons (cf. also references in Berezinsky et al. 1990). At very high energies protons scatter inelastically by photo-production of secondaries, i.e. $p + \gamma \rightarrow \pi^0 + p$ and $p + \gamma \rightarrow e^+ + e^- + p$. In contrast to the low-density interstellar medium where $\gamma$-rays can escape freely, blazars absorb the energetic $\gamma$-rays resulting from the decay of secondaries via pair creation $\gamma + \gamma \rightarrow e^+ + e^-$. As a consequence, unsaturated pair cascades develop which attenuate the $\gamma$-ray flux above the energy $\epsilon^*$ where $\tau_{\gamma\gamma}(\epsilon^*) = 1$, but which let $\gamma$-rays with energies $\epsilon < \epsilon^*$ escape freely (Mannheim et al. 1991).

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Only if the particles responsible for the $\gamma$-ray emission are accelerated very close to the AGN, so that the energy density of the external radiation field exceeds that intrinsic to the jet, inverse-Compton scattering becomes the dominant cooling mechanism. Sikora et al. (1994) have argued that the re-radiation of a central thermal UV spectrum by the broad emission line clouds can produce such a strong external radiation field, if the $\gamma$-ray production occurs within the central parsec of the AGN powering the $\gamma$-ray blazar. Dermer et al. (1992) have argued that direct thermal radiation from an accretion disk represents the majority of target photons. It was predicted by the latter model that spectral breaks greater than $\Delta s = 0.5$ should not occur in the $\gamma$-ray regime — in contrast to the observations. Also required
is the presence of a source of thermal target radiation dominating the bolometric luminosity, although no indication of this big blue bump spectral component is seen in the spectra of several blazars with a near-infrared/optical cut-off (Bregman 1990). It is a fundamental question, whether or not such a thermal emission component is ubiquitous in AGN. Indeed, the emission component can remain undiscovered due to Doppler boosting of the nonthermal luminosity by factors $> 10^4$ or due to obscuration by dust. If, however, obscuration is responsible for hiding the thermal source, it would also be hidden for the relativistic particles in the jet. Consequently, nonthermal optical outbursts should not occur simultaneously with $\gamma$-ray outbursts.

Another limitation of these models is that the extreme inverse-Compton losses postulated imply that an unknown impulsive electron acceleration mechanism must be operating. Magnetic reconnection could be such a process. However, the thickness of neutral sheets is probably insufficient to obtain the large potential drops required for the great values of the electron Lorentz factors. It is also unclear, whether the observed power law electron spectra can be produced in this way.

1.3. Proton-induced cascades

In the most simple model for blazar emission it is assumed that steady, conical relativistic jets of Lorentz factor $\gamma_j$ with opening angle $\Phi \approx \gamma_j^{-1}$ are viewed at a small angle $\theta$ (Blandford & Königl 1979, Mannheim 1993a). Photons emitted isotropically in the comoving frame are blueshifted with the Doppler factor $\delta = [\gamma(1-\beta \cos \theta)]^{-1}$ and the apparent luminosity exceeds the comoving frame luminosity by a large margin. The outflow is assumed to advect a tangled magnetic field and relativistic particles in equipartition with the magnetic field. Most probably shock acceleration compensates adiabatic losses during the expansion. Synchrotron-self-absorption frequency, break frequency (above which the cooling time scale is shorter than the dynamical time scale) and emissivity obey a simple scaling with distance $r$ along the jet, such that the superposition of spectra from scales between $r_{\text{min}}$ and $r_{\text{max}}$ yields a flat spectrum $S_{\nu} \propto \text{const.}$ up to the break frequency $\nu_b \approx 10^{11} - 10^{13}$ Hz above which the spectrum steepens by one power yielding $S_{\nu} \propto \nu^{-1}$. In the near-infrared/soft X-ray regime the primary electron synchrotron spectrum turns over steeply when the cooling time scale becomes shorter than the acceleration time scale. For protons, the break energy is reached at

$$\gamma_{p,b} = \left( \frac{m_p}{m_e} \right)^{\frac{3}{2}} \frac{1 + a}{1 + 240a} \gamma_{e,b} \approx 3 \cdot 10^9 \left( \frac{\gamma_{e,b}}{100} \right)$$

(1)

Note that $a = u_e/u_B$ refers only to the synchrotron photon density in the radio through X-ray range, since higher energy photons are unimportant as a target, for inverse-Compton scattering because of the Klein-Nishina cross-section and for photo-production because of the threshold energy. The proton break energy is much greater than the electron break energy, since the proton energy losses are negligible compared to the electron energy losses at the same energy. The proton-induced luminosity for $\gamma_p \leq \gamma_{p,b}$ has the value

$$L_{\text{casc}} \approx \eta \left( \frac{\gamma_p}{\gamma_{p,b}} \right) L_{\text{syn}}$$

(2)
where $\eta = u_p/u_e$ denotes the energy density ratio of relativistic protons and electrons, respectively. It is very likely that protons do not always reach the extremely high energy $\gamma_p = \gamma_{p,b}$. One limitation arises from the condition that the proton Larmor radius must remain smaller than the shock radius which is itself less than the jet radius (Bell 1978). Hence it follows that for a universal cosmic ray proton/electron ratio $\eta$ it is the proton maximum energy which determines the $\gamma$-ray spectrum.

The brightest $\gamma$-ray emission is expected from the most compact parts of the jet where most of the nonthermal target photons with $\nu \geq \nu_b$ are produced, i.e. at the jet length $r = r_b$ (jet radius $r_{b,1} \approx r_b \Phi$). At smaller scales $r < r_b$ synchrotron-self-absorption and rapid dynamical evolution darken the jet, whereas at larger scales $r > r_b$ the radio flux increases and the infrared photon flux decreases. Due to the threshold condition for secondary particle production, e.g. $\nu_{th} \geq 2 \cdot 10^{12}(\gamma_p/10^{10})^{-1}$ Hz for pions, only the infrared and higher frequency photons are relevant as a target for the protons. Indeed, the jet would be $\gamma$-ray bright also on large scales (steep spectrum radio sources), if the proton maximum energy were allowed to reach up to a value $\gamma_p \geq \gamma_{p,b}$ at any scale in the jet. However, this is impossible due to the Larmor radius constraint and the finite acceleration time scale. The greatest values of the proton maximum energy seem to be achieved in the hot spots of radio galaxies where $\gamma_{p,max} \approx 3 \cdot 10^{11} \approx 0.7\gamma_{p,b}$ (Biermann & Strittmatter 1987). Notice, however, that blazars with $L_\gamma \approx 100 L_{syn}$ require $\gamma_p = \gamma_{p,b} \approx 10^{10} (\eta = 100)$ in the compact parts of the blazar jet. Some of these protons escape after isospin flip $p + \gamma \rightarrow n + \pi^+$ as neutrons. The neutrons then suffer $\beta$-decay at a distance of $d_n = \tau_n c \gamma_n \approx 100$ kpc from the blazar. In this way an extragalactic proton flux without adiabatic losses is injected into the intergalactic medium. In the observer’s frame these particles have a Lorentz factor $\gamma \approx \delta \gamma_{p,b} \approx 10^{11}$.

Tacitly it is assumed that the jets become radiative at a rather large distance from their origin. Shocks are generated as the jet propagates through the external steep pressure gradient of the elliptical host galaxy. This could happen at a distance as far as 1 kpc from the kinematical center (Sanders 1983).

The spectrum of the proton-induced cascades is complex, producing broken power laws and double-humped spectra between X-ray energies and 100 TeV (Mannheim et al. 1991). The internal absorption of $\gamma$-rays in ‘proton blazars’ (Mannheim 1993a), which determines the precise shape of the cascade spectrum, is difficult to assess, since the photon density is highly inhomogenous, e.g. varying from the limb to the center of the jet and varying with length along the jet. However, the effective compactness is strongly constrained once the cascade spectrum is known from observations between keV and GeV photon energies.

Since proton-induced cascades inject electromagnetic energy at ultra-high energies, it is, in fact, the strongest implication of the proton blazar model that TeV $\gamma$-ray emission can be regarded as a typical property. This is in marked contrast to the leptonic models where physical parameters have to be pushed to their limits. The best candidate sources for TeV detection are $\gamma$-ray sources with a hard X-ray spectral index $\alpha_x = 0.5 - 0.7$ indicating a low comoving frame radiation compactness.
1.4. Merits of γ-ray measurements

External absorption of γ-rays by the infrared/optical radiation field produced inside the blazar host galaxy (Mannheim 1993b) and by the cosmic background radiation produced by all galaxies (Gould & Schrédéer 1966, Stecker et al. 1992, MacMinn & Primack 1994) must be taken into account. This limits the number of possible TeV sources to the few nearest blazars, but it opens up new and challenging possibilities for probing the era of galaxy formation and the cosmic distance scale, since \( \tau_{\gamma\gamma}(\epsilon_{\gamma}) \propto n_{ir}(\epsilon_{\gamma})H_0^{-1} \) where \( n_{ir}(\epsilon_{\gamma}) \) is the near-infrared photon density at the pair creation threshold \( \epsilon_0 = 2(m_e c^2)^2/\epsilon_{\gamma} \simeq 0.5/(\epsilon_{\gamma}/\text{TeV}) \text{ eV} \). A prerequisite for measuring either \( H_0 \) or \( n_{ir} \) via the exponential cut-off produced by external absorption is a theoretical prediction of the unabsorbed γ-ray spectra. To this end I discuss below the γ-ray spectra of 1219+285 and Mrk421 in some detail. The strategy is to find combined electron synchrotron spectra and cascade spectra fitting to the multifrequency data for the same set of parameters. In this way the spectrum is highly constrained yielding firm predictions for the TeV range.

2. TeV emission from Mrk421 and 1219+285

Internal absorption of γ-rays inside the blazar jets is crucial to the shape of the emerging radiation spectrum. For a steady jet the optical depth in the comoving frame is given by

\[
\tau_{\gamma\gamma} = \int_{2(m_e c^2)^2/\epsilon_{\gamma}}^{\infty} n_{\text{syn}}(\epsilon) \sigma_{\gamma\gamma}(\epsilon, \epsilon_{\gamma}) r_{b,\perp} d\epsilon \propto \frac{a B^2 \epsilon_{\gamma}}{8\pi \ln[\epsilon_{\epsilon}/\epsilon_{b}](m_e c^2)^2} \frac{\sigma_T}{3} r_{b,\perp} \tag{3}
\]

where \( a \simeq (1 + \eta)^{-1} \beta \gamma_{\text{jet}} \Phi \approx (1 + \eta)^{-1} \). Above the comoving frame energy \( \epsilon^* \) where \( \tau_{\gamma\gamma}(\epsilon^*) = 1 \) the cascade spectrum steepens by one power, since

\[
I_{\gamma} = I_{\gamma_{\min}} \frac{1 - \exp[-\tau_{\gamma\gamma}]}{\tau_{\gamma\gamma}} \rightarrow I_{\gamma_{\min}} \epsilon_{\gamma}^{-1} (\tau_{\gamma\gamma} \gg 1) \tag{4}
\]

From the proton blazar model fits shown in Figs. 1,2 obtained for the parameters in Tab. 1 one can infer that the turnover energies in the observer’s frame \( \delta \epsilon_{\gamma} \) are of the order of TeV, viz.

\[
\epsilon_{\gamma_{\min}}(\text{obs}) \approx \left( \frac{\delta}{10} \right) \left( \frac{\ln[\epsilon_{\epsilon}/r_{b}]}{6} \right) \left( \frac{\eta}{100} \right) \left( \frac{B}{10 \text{ G}} \right)^{-2} \left( \frac{r_{b,\perp}}{3 \cdot 10^{15} \text{ cm}} \right)^{-1} \text{ TeV} \tag{5}
\]

It is the length scale \( r = r_{b} \) where the jet becomes optically thin for infrared radiation which regulates the internal absorption to values such that TeV is the typical turnover energy. Another typical energy can be found as a direct consequence: Pairs produced from the optically thick part of the cascade at \( \epsilon_{\gamma} \) have Lorentz factors \( \gamma_{e} = \epsilon_{\gamma}/2 \). The synchrotron photons from these pairs have characteristic energies

\[
\epsilon_{\gamma_{\min}}(\text{obs}) = 3 \cdot 10^{-14} \delta B (\gamma_{e})^2 \approx 0.02 \left( \frac{\delta}{10} \right)^{-1} \left( \frac{B}{10 \text{ G}} \right) \left( \frac{\epsilon_{\gamma_{\min}}(\text{obs})}{\text{TeV}} \right)^2 \text{ MeV} \tag{6}
\]
Below this energy the unsaturated cascade is optically thin, so that the typical X-ray spectral index is $\alpha_X = 0.5 - 0.7$ in marked contrast to saturated cascades with $\alpha_X = 0.9 - 1.0$ (Svensson 1987).

No definite predictions for the proton blazar spectra during flux outbursts can be made at present, since this would require to solve non-stationary cascade equations and to couple the radiative transport with a dynamical model for shock propagation and particle acceleration. Most probably, outbursts represent shocks propagating into the optically thin part of the jet. The optical outbursts (primary electrons) and the hard X-/\gamma-ray outbursts (cascade pairs) should be correlated, since the cascades develop in the synchrotron photon target produced by the primary electrons. The high-energy cascade emission therefore follows the optical outburst on the very short proton photo-production cooling time scale. This time scale is larger than the optical outburst decay time scale by a factor of $\approx \eta/R = L_\gamma/L_\circ$ where $R \equiv L_\gamma/L_\circ$ denotes the \gamma/optical luminosity ratio, cf. Eq.(2). If there is a universal value of the proton/electron ratio $\eta$, it is predicted that the sources with weakest \gamma-ray emission compared to the optical emission display the largest delays in \gamma-rays.

| TABLE I |

Physical parameters for the proton blazar model fits shown in Figs. 1,2. See Mannheim (1993a) for further explanations

|        | 1219+285 | Mrk421 |
|--------|----------|--------|
| $B$ [G] | 4        | 40     |
| $\eta$ | 30       | 100    |
| $r_{b,\perp}$ [cm] | $7 \cdot 10^{15}$ | $2 \cdot 10^{15}$ |
| $\gamma_p$ | $2 \cdot 10^9$ | $6 \cdot 10^7$ |
| $\delta$ | 7        | 31     |
| $\gamma_j$ | 5        | 20     |
| $\theta$ [deg] | 7        | 1.5    |
| $L_{44}$ | 30       | 18     |
| $\gamma_p/\gamma_{p,b}$ | $3 \cdot 10^{-2}$ | $5 \cdot 10^{-4}$ |

3. Discussion and conclusions

Abundaning geocentrism it is hard to conceive that baryonic cosmic rays should not be present in radio jets. Requiring the Larmor radii of protons to be smaller than the jet radius yields a maximum energy of up to $10^{11}$ GeV – large enough to make extragalactic radio jets the source of cosmic rays above EeV (Rachen & Biermann 1993).

Recent \gamma-ray measurements in the energy band $0.1 - 10$ GeV have established that the brightest and most compact extragalactic jets are indeed powerful cosmic particle accelerators with their maximum luminosity temporarily in the \gamma-ray band. Proton-induced unsaturated synchrotron cascades can be responsible for the observed \gamma-ray emission. In marked contrast to the relativistic protons, for which
energy losses become important only near their maximum energy, electrons suffer severe energy losses during the entire acceleration process which hinders them to reach the high Lorentz factors needed to produce ample TeV photons by inverse-Compton scattering of UV-photons. Therefore, TeV $\gamma$-ray emission can be considered as a typical indicator of proton acceleration in radio jets.

However, nature has limited our view of the universe by a very restricted horizon for $\gamma$-ray eyes. Due to pair-absorption of $\gamma$-rays on cosmic background radiation fields the TeV world ends at a luminosity distance of roughly 400 Mpc. Only the few nearest blazars are therefore potential TeV sources. Nevertheless, the precise value of the TeV horizon depends on two quantities of superior astrophysical interest: The Hubble-constant and the near-infrared photon density which entails the conditions at birth of normal galaxies. We may hope to shed more light on these cosmological cornerstones by measuring and analysing the TeV $\gamma$-ray spectra of nearby blazars.

Neglecting the non-simultaneity of the multifrequency data and on the basic assumptions of the proton blazar model (biconical relativistic outflow, isotropy of ultra-relativistic particles in the comoving frame, equipartition of relativistic...
Fig. 2. Multifrequency spectrum of Mrk421 obtained from the NED, von Montigny et al. (1994), Punch et al. (1992), Thomas (priv.com.), Kühn (1994) and Karle (1994). The solid line shows the proton blazar model fit for the parameter values in Tab. 1. The dashed line shows the expected flux accounting for external absorption (Stecker et al. 1992)

particle energy and magnetic field energy) I was able to obtain flux predictions in the air Cherenkov energy range and above for two nearby blazars Mrk421 (z = 0.308) and 1218+285 (z = 0.102).

In the TeV range internal absorption of γ-rays producing a break in the power-law spectrum competes with external absorption producing an exponential cut-off. The observed TeV γ-ray emission from Mrk421 is consistent with little external absorption, whereas significant external absorption is likely to be present in the spectrum of 1219+285. If the Hubble-constant had a value \( H_0 \geq 75 \text{ km/s/Mpc} \) or if the near-infrared photon density had a value less than the expected value \( n_\gamma(0.5\text{eV}) \approx 2 \cdot 10^{-3} \text{ cm}^{-3} \), the proton-induced cascade flux would have been above the Whipple upper limit for this source. However, since external absorption does not decrease the observed flux in the air Cherenkov energy range by a large factor, 1219+285 is very likely to be the next blazar detected by a Cherenkov telescope.
Acknowledgements

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Only if the particles responsible for the γ-ray emission are accelerated very close to the AGN, so that the energy density of the external radiation field exceeds that intrinsic to the jet, inverse-Compton scattering becomes the dominant cooling mechanism. Sikora et al. (1994) have argued that the re-radiation of a central thermal UV spectrum by the broad emission line clouds can produce such a strong external radiation field, if the γ-ray production occurs within the central parsec of the AGN powering the γ-ray blazar. Dermer et al. (1992) have argued that direct thermal radiation from an accretion disk represents the majority of target photons. It was predicted by the latter model that spectral breaks greater than $\Delta s = 0.5$ should not occur in the γ-ray regime – in contrast to the observations. Also required is the presence of a source of thermal target radiation dominating the bolometric luminosity, although no indication of this big blue bump spectral component is seen in the spectra of several blazars with a near-infrared/optical cut-off (Bregman 1990). It is a fundamental question, whether or not such a thermal emission component is ubiquitous in AGN. Indeed, the emission component can remain undiscovered due to Doppler boosting of the nonthermal luminosity by factors $> 10^4$ or due to obscuration by dust. If, however, obscuration is responsible for hiding the thermal source, it would also be hidden for the relativistic particles in the jet. Consequently, nonthermal optical outbursts should not occur simultaneously with γ-ray outbursts. Another limitation of these models is that the extreme inverse-Compton losses postulated imply that an unknown impulsive electron acceleration mechanism must be operating. Magnetic reconnection could be such a process. However, the thickness of neutral sheets is probably insufficient to obtain the large potential drops required for the great values of the electron Lorentz factors. It is also unclear, whether the observed power law electron spectra can be produced in this way.

1.3. Proton-induced cascades

In the most simple model for blazar emission it is assumed that steady, conical relativistic jets of Lorentz factor $\gamma_j$ with opening angle $\Phi \approx \gamma_j^{-1}$ are viewed at a small angle $\theta$ (Blandford & Königl 1979, Mannheim 1993a). Photons emitted isotropically in the comoving frame are blueshifted with the Doppler factor $\delta = [\gamma(1 - \beta \cos \theta)]^{-1}$ and the apparent luminosity exceeds the comoving frame luminosity by a large margin. The outflow is assumed to advect a tangled magnetic field and relativistic particles in equipartition with the magnetic field. Most probably shock acceleration compensates adiabatic losses during the expansion. Synchrotron-self-absorption frequency, break frequency (above which the cooling time scale is shorter than the dynamical time scale) and emissivity obey a simple scaling with distance $r$ along the jet, such that the superposition of spectra from scales between $r_{\text{min}}$ and $r_{\text{max}}$ yields a flat spectrum $S_\nu \propto \text{const.}$ up to the break frequency $\nu_b \approx 10^{11} -$
$10^{13}$ Hz above which the spectrum steepens by one power yielding $S_\nu \propto \nu^{-1}$. In the near-infrared/soft X-ray regime the primary electron synchrotron spectrum turns over steeply when the cooling time scale becomes shorter than the acceleration time scale. For protons, the break energy is reached at

$$\gamma_{p,b} = \left( \frac{m_p}{m_e} \right)^3 \frac{1 + a}{1 + 240a} \gamma_{e,b} \approx 3 \cdot 10^9 \left( \frac{\gamma_{e,b}}{100} \right)$$

(1)

Note that $a = u_e/u_B$ refers only to the synchrotron photon density in the radio through X-ray range, since higher energy photons are unimportant as a target, for inverse-Compton scattering because of the Klein-Nishina cross-section and for photo-production because of the threshold energy. The proton break energy is much greater than the electron break energy, since the proton energy losses are negligible compared to the electron energy losses at the same energy. The proton-induced luminosity for $\gamma_p \leq \gamma_{p,b}$ has the value

$$L_{\text{casc}} \approx \eta \left( \frac{\gamma_p}{\gamma_{p,b}} \right) L_{\text{syn}}$$

(2)

where $\eta = u_p/u_e$ denotes the energy density ratio of relativistic protons and electrons, respectively. It is very likely that protons do not always reach the extremely high energy $\gamma_p = \gamma_{p,b}$. One limitation arises from the condition that the proton Larmor radius must remain smaller than the shock radius which is itself less than the jet radius (Bell 1978). Hence it follows that for a universal cosmic ray proton/electron ratio $\eta$ it is the proton maximum energy which determines the $\gamma$-ray spectrum.

The brightest $\gamma$-ray emission is expected from the most compact parts of the jet where most of the nonthermal target photons with $\nu \geq \nu_b$ are produced, i.e. at the jet length $r = r_b$ (jet radius $r_{b,\perp} \approx r_b\Phi$). At smaller scales $r < r_b$ synchrotron-self-absorption and rapid dynamical evolution darken the jet, whereas at larger scales $r > r_b$ the radio flux increases and the infrared photon flux decreases. Due to the threshold condition for secondary particle production, e.g. $\nu_{\text{th}} \geq 2 \cdot 10^{12}(\gamma_p/10^{10})^{-1}$ Hz for pions, only the infrared and higher frequency photons are relevant as a target for the protons. Indeed, the jet would be $\gamma$-ray bright also on large scales (steep spectrum radio sources), if the proton maximum energy were allowed to reach up to a value $\gamma_p \geq \gamma_{p,b}$ at any scale in the jet. However, this is impossible due to the Larmor radius constraint and the finite acceleration time scale. The greatest values of the proton maximum energy seem to be achieved in the hot spots of radio galaxies where $\gamma_{p,max} \approx 3 \cdot 10^{11} \approx 0.07 \gamma_{p,b}$ (Biermann & Strittmatter 1987). Notice, however, that blazars with $L_\gamma \approx 100L_{\text{syn}}$ require $\gamma_p = \gamma_{p,b} \approx 10^{10}$ ($\eta = 100$) in the compact parts of the blazar jet. Some of these protons escape after isospin flip $p + \gamma \rightarrow n + \pi^+$ as neutrons. The neutrons then suffer $\beta$-decay at a distance of $d_n = \tau_n c \gamma_n \approx$
100 kpc from the blazar. In this way an extragalactic proton flux without adiabatic losses is injected into the intergalactic medium. In the observer’s frame these particles have a Lorentz factor \( \gamma \approx \delta \gamma_p \approx 10^{11} \).

Tactily it is assumed that the jets become radiative at a rather large distance from their origin. Shocks are generated as the jet propagates through the external steep pressure gradient of the elliptical host galaxy. This could happen at a distance as far as 1 kpc from the kinematical center (Sanders 1983).

The spectrum of the proton-induced cascades is complex, producing broken power laws and double-humped spectra between X-ray energies and 100 TeV (Mannheim et al. 1991). The internal absorption of \( \gamma \)-rays in ‘proton blazars’ (Mannheim 1993a), which determines the precise shape of the cascade spectrum, is difficult to assess, since the photon density is highly inhomogenous, e.g. varying from the limb to the center of the jet and varying with length along the jet. However, the effective compactness is strongly constrained once the cascade spectrum is known from observations between keV and GeV photon energies.

Since proton-induced cascades inject electromagnetic energy at ultra-high energies, it is, in fact, the strongest implication of the proton blazar model that TeV \( \gamma \)-ray emission can be regarded as a typical property. This is in marked contrast to the leptonic models where physical parameters have to be pushed to their limits. The best candidate sources for TeV detection are \( \gamma \)-ray sources with a hard X-ray spectral index \( \alpha_x = 0.5 - 0.7 \) indicating a low comoving frame radiation compactness.

1.4. **Merits of \( \gamma \)-ray measurements**

External absorption of \( \gamma \)-rays by the infrared/optical radiation field produced inside the blazar host galaxy (Mannheim 1993b) and by the cosmic background radiation produced by all galaxies (Gould & Schréder 1966, Stecker et al. 1992, MacMinn & Primack 1994) must be taken into account. This limits the number of possible TeV sources to the few nearest blazars, but it opens up new and challenging possibilities for probing the era of galaxy formation and the cosmic distance scale, since \( \tau_{\gamma\gamma}(\epsilon_\gamma) \propto n_{ir}(\epsilon_\gamma) H_\odot^{-1} \) where \( n_{ir}(\epsilon_\gamma) \) is the near-infrared photon density at the pair creation threshold \( \epsilon_0 = 2(m_e c^2)^2/\epsilon_\gamma \approx 0.5/(\epsilon_\gamma/\text{TeV}) \text{eV} \). A prerequisite for measuring either \( H_\odot \) or \( n_{ir} \) via the exponential cut-off produced by external absorption is a theoretical prediction of the unabsorbed \( \gamma \)-ray spectra. To this end I discuss below the \( \gamma \)-ray spectra of 1219+285 and Mrk421 in some detail. The strategy is to find combined electron synchrotron spectra and cascade spectra fitting to the multifrequency data for the same set of parameters. In this way the spectrum is highly constrained yielding firm predictions for the TeV range.
2. TeV emission from Mrk421 and 1219+285

Internal absorption of γ-rays inside the blazar jets is crucial to the shape of the emerging radiation spectrum. For a steady jet the optical depth in the comoving frame is given by

\[
\tau_{\gamma\gamma} = \int_0^\infty \frac{n_{\text{syn}}(\epsilon)\sigma_{\gamma\gamma}(\epsilon, \epsilon_{\gamma}) r_{b,1} d\epsilon}{2(\Delta e^2) / c, \gamma_{\mu}} \approx \frac{\alpha B^2 c_{\gamma}^*}{8\pi \ln[c_{\mu}/c_{b}](m_e c^2)^2} \frac{\sigma_{T}}{3} r_{b,1} (3)
\]

where \( a \approx (1 + \eta)^{-1/2} \gamma_{\gamma}^* \Phi \approx (1 + \eta)^{-1} \). Above the comoving frame energy \( \epsilon^* \) where \( \tau_{\gamma\gamma}(\epsilon^*) = 1 \) the cascade spectrum steepens by one power, since

\[
I_\gamma = I_\gamma^\circ \left(1 - \exp \left[-\frac{\tau_{\gamma\gamma}}{\tau_{\gamma\gamma}}\right]\right) \to I_\gamma^\circ \epsilon_{\gamma}^{-1} \quad (\tau_{\gamma\gamma} \gg 1)
\]

From the proton blazar model fits shown in Figs. 1,2 obtained for the parameters in Tab. 1 one can infer that the turnover energies in the observer’s frame \( \delta c_{\gamma}^* \) are of the order of TeV, viz.

\[
c_{\gamma}^*(\text{obs}) \approx \left(\frac{\delta}{10}\right) \left(\frac{\ln[c_{\mu}/c_{b}]}{6}\right) \left(\frac{\eta}{100}\right) \left(\frac{B}{10 \text{ G}}\right)^{-2} \left(\frac{r_{b,1}}{3 \times 10^{15} \text{ cm}}\right)^{-1} \text{ TeV (5)}
\]

It is the length scale \( r = r_{b} \) where the jet becomes optically thin for infrared radiation which regulates the internal absorption to values such that TeV is the typical turnover energy. Another typical energy can be found as a direct consequence: Pairs produced from the optically thick part of the cascade at \( c_{\gamma}^* \) have Lorentz factors \( \gamma_{\epsilon}^* = c_{\gamma}^*/2 \). The synchrotron photons from these pairs have characteristic energies

\[
c_{\gamma}^{\epsilon*}(\text{obs}) = 3 \times 10^{-14} B (\gamma_{\epsilon}^*)^2 \approx 0.02 \left(\frac{\delta}{10}\right)^{-1} \left(\frac{B}{10 \text{ G}}\right) \left(\frac{c_{\gamma}^*(\text{obs})}{\text{TeV}}\right)^2 \text{ MeV (6)}
\]

Below this energy the unsaturated cascade is optically thin, so that the typical X-ray spectral index is \( \alpha_X = 0.5 - 0.7 \) in marked contrast to saturated cascades with \( \alpha_X = 0.9 - 1.0 \) (Svensson 1987).

No definite predictions for the proton blazar spectra during flux outbursts can be made at present, since this would require to solve non-stationary cascade equations and to couple the radiative transport with a dynamical model for shock propagation and particle acceleration. Most probably, outbursts represent shocks propagating into the optically thin part of the jet. The optical outbursts (primary electrons) and the hard X-/γ-ray outbursts (cascade pairs) should be correlated, since the cascades develop in the synchrotron photon target produced by the primary electrons. The high-energy cascade emission therefore follows the optical outburst on the very short proton photo-production cooling time scale. This time scale is larger than the optical outburst decay time scale by a factor of \( \approx \eta/R \) where \( R = L/\dot{L} \).
denotes the $\gamma$/optical luminosity ratio, cf. Eq.(2). If there is a universal value of the proton/electron ratio $\eta$, it is predicted that the sources with weakest $\gamma$-ray emission compared to the optical emission display the largest delays in $\gamma$-rays.

| TABLE I |
| --- |
| Physical parameters for the proton blazar model fits shown in Figs. 1, 2. See Mannheim (1993a) for further explanations |
| 1219+285 | Mrk421 |
| $B$ [G] | 4 | 40 |
| $\eta$ | 30 | 100 |
| $r_{b,\perp}$ [cm] | $7 \cdot 10^{15}$ | $2 \cdot 10^{15}$ |
| $\gamma_p$ | $2 \cdot 10^9$ | $6 \cdot 10^7$ |
| $\delta$ | 7 | 31 |
| $\gamma_l$ | 5 | 20 |
| $\theta$ [deg] | 7 | 1.5 |
| $L_{44}$ | 30 | 18 |
| $\gamma_p/\gamma_{p,b}$ | $3 \cdot 10^{-2}$ | $5 \cdot 10^{-4}$ |

3. Discussion and conclusions

Abundaning geocentrism it is hard to conveive that baryonic cosmic rays should not be present in radio jets. Requiring the Larmor radii of protons to be smaller than the jet radius yields a maximum energy of up to $10^{12}$ GeV – large enough to make extragalactic radio jets the source of cosmic rays above EeV (Rachen & Biermann 1993).

Recent $\gamma$-ray measurements in the energy band $0.1 - 10$ GeV have established that the brightest and most compact extragalactic jets are indeed powerful cosmic particle accelerators with their maximum luminosity temporarily in the $\gamma$-ray band. Proton-induced unsaturated synchrotron cascades can be responsible for the observed $\gamma$-ray emission. In marked contrast to the relativistic protons, for which energy losses become important only near their maximum energy, electrons suffer severe energy losses during the entire acceleration process which hinders them to reach the high Lorentz factors needed to produce ample TeV photons by inverse-Compton scattering of UV-photons. Therefore, TeV $\gamma$-ray emission can be considered as a typical indicator of proton acceleration in radio jets.

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Fig. 1. Multifrequency spectrum of 1219+285. Data were obtained from the NED, von Montigny et al. (1994), Fink (priv.com.) and the Whipple group (priv.com.). The solid line shows the proton blazar model fit for the parameter values in Tab. 1. The dashed line shows the expected flux accounting for external absorption (Stecker et al. 1992)

However, nature has limited our view of the universe by a very restricted horizon for γ-ray eyes. Due to pair-absorption of γ-rays on cosmic background radiation fields the TeV world ends at a luminosity distance of roughly 400 Mpc. Only the few nearest blazars are therefore potential TeV sources. Nevertheless, the precise value of the TeV horizon depends on two quantities of superior astrophysical interest: The Hubble-constant and the near-infrared photon density which entails the conditions at birth of normal galaxies. We may hope to shed more light on these cosmological cornerstones by measuring and analysing the TeV γ-ray spectra of nearby blazars.

Neglecting the non-simultaneity of the multifrequency data and on the basic assumptions of the proton blazar model (biconical relativistic outflow, isotropy of ultra-relativistic particles in the comoving frame, equipartition of relativistic particle energy and magnetic field energy) I was able to obtain flux predictions in the air Cherenkov energy range and above for two nearby blazars Mrk421 (z = 0.308) and 1218+285 (z = 0.102).
In the TeV range internal absorption of $\gamma$-rays producing a break in the power-law spectrum competes with external absorption producing an exponential cut-off. The observed TeV $\gamma$-ray emission from Mrk421 is consistent with little external absorption, whereas significant external absorption is likely to be present in the spectrum of 1219+285. If the Hubble-constant had a value $H_0 \geq 75$ km/s/Mpc or if the near-infrared photon density had a value less than the expected value $n_\gamma(0.5\text{eV}) \approx 2 \cdot 10^{-3}$ cm$^{-3}$, the proton-induced cascade flux would have been above the Whipple upper limit for this source. However, since external absorption does not decrease the observed flux in the air Chérénkov energy range by a large factor, 1219+285 is very likely to be the next blazar detected by a Chérénkov telescope.
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