AGN Models: High-Energy Emission

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Astrophysical models for the high-energy emission of blazars are reviewed. Blazars ejecting relativistic radio jets at small angles to the line-of-sight are the only type of active galactic nuclei (AGN) discovered above 100 MeV. The $\gamma$-rays apparently originate in the jets which explains the absence of $\gamma$-ray pair creation attenuation. The bulk Lorentz factor of the radio jets is much smaller than the Lorentz factors of the emitting particles requiring in situ particle acceleration such as Fermi acceleration at shocks. The mounting evidence for a correlation between the optical and $\gamma$-ray emission argues for the same accelerated electrons emitting the polarized optical synchrotron photons to be responsible for the high-energy emission. Alternatively, the $\gamma$-rays could be due to electrons of a secondary origin related to the energy losses of protons accelerated at the same shocks as the synchrotron emitting electrons. In this case blazars would produce an observable flux of high-energy neutrinos. Unified schemes for AGN predict a circum-nuclear warm dust torus attenuating $\gamma$-rays above $\sim 300$ GeV emitted from within a central sphere of radius $\sim 2 \times 10^4 r_S$ which rules out external Compton scattering models as the origin of the TeV $\gamma$-rays from Mrk421 and Mrk501.

1 Introduction

The EGRET discovery of $\gamma$-ray sources at high galactic latitudes and their identification with blazars ($\sim$ flat-spectrum radio-loud AGN) has prompted a large number of authors to think about possible explanations for the phenomenon. As of 1996, I have counted almost one model or one model ramification per source scanning through NASA’s Astrophysics Data System. The considerable theoretical interest documents the importance of the discovery and at the same time demonstrates the on-going struggle for a viable explanation. Of course, not all of the papers can be discussed in this review, and I have decided to critically discuss only the basic model assumptions and their consequences. The assumptions that (i) blazars represent accreting supermassive black holes ejecting bipolar jets along the angular momentum axis of the inner accretion disk and that (ii) the $\gamma$-rays originate in the jets are common to all the models. This consensus is based mainly on the facts that EGRET has observed $\gamma$-rays only from AGN with jets and that jets provide a natural resolution of the so-called compactness problem: For $\gamma$-rays of energy $m_e c^2$ the pair creation optical depth $\gamma + \gamma \rightarrow e^+ + e^-$ of an Eddington accreting black hole is the universal constant

$$\tau_{\gamma\gamma} \simeq \frac{L_{\text{edd}}}{4\pi r_S m_e c^3} \frac{3\sigma_T}{16} = \frac{3}{32} \frac{m_p}{m_e} \simeq 200$$

Eddington accretion onto a supermassive black hole is the only mechanism efficient enough to explain the high luminosities and short variability time scales of blazars assuming isotropic emission. However, the large optical depth Eq.(1) is inconsistent with the observed optically thin power law spectra and therefore the emission must be anisotropic.
The accreting black hole picture for blazars is based on unified schemes for AGN which are discussed extensively in the contribution by Padovani. As a general cautious remark I want to emphasize that the predictions of the unified schemes for the density of matter and radiation in the medium surrounding the jets are subject to change in the course of further astronomical studies and should therefore be regarded as preliminary. Furthermore, the unified schemes leave it essentially open whether the jets form as a hydromagnetic $e^-p$ wind from the relativistic inner accretion disk or as a Poynting flux driven $e^\pm$ wind extracting rotational energy from the central black hole. The merging history of ellipticals as the typical host galaxies of radio-loud AGN lends some support for the rotating black hole picture, although jets are also associated with young stars which do not contain black holes. It is hoped that the $\gamma$-ray properties of blazars probing the physical conditions in the jets ameliorate theory in this important issue. However, baryon pollution could also wash out the difference between pair winds and $e^-p$ disk winds.

1.1 Relativistic particles, cold and hot beams, internal and external target photons

By analogy with the local cosmic rays, the relativistic particles responsible for the $\gamma$-rays are expected to be electrons and protons. In the tenuous plasma of the jets, electrons (positrons) produce $\gamma$-rays mainly by inverse-Compton scattering or synchrotron emission. For protons these processes are generally unimportant owing to their larger mass. The pion production on matter, which is important as a $\gamma$-ray production process in the Galaxy, can be neglected due to the low plasma density in radio jets. However, the photo-production of secondary pions and pairs in collisions with ambient low-energy photons can be important. In spite of the hadronic cross-section $\sigma_{p\gamma} = 5 \times 10^{-28}$ cm$^2$ being much smaller than the Thomson cross-section $\sigma_T = 6.7 \times 10^{-25}$ cm$^2$, the proton cooling time scale can be as short as the electron Thomson cooling time scale owing to the much larger inelasticity of hadronic processes. The proton and electron energy losses ($i = e,p$) are given by

$$- \frac{dE_i}{dt} = \frac{4}{3} \sigma_T \left( \frac{m_e}{m_i} \right)^2 \frac{B^2}{8\pi \gamma_i^2} f_i c$$

(2)
where the factors \( f_e = 1 + u_\gamma / u_B \) and \( f_p = 1 + 500 u_\gamma / u_B \) take into account the relative contribution of synchrotron, inverse Compton, Bethe-Heitler pair production, and pion production. Balancing with energy gains due to Fermi acceleration

\[
\frac{dE}{dt} = K ec^2 B
\]

where \( K < 0.4 \) depends on the diffusion coefficients one obtains the maximum Lorentz factors

\[
\gamma_{p,\text{max}} = 7 \times 10^{10} K^{1/2} B^{-1/2} f_p^{-1/2}
\]

for protons and

\[
\gamma_{e,\text{max}} = 4 \times 10^7 K^{1/2} B^{-1/2} f_p^{-1/2}
\]

for electrons. Adopting \( K = 0.1, B = 1 \text{ G}, \) and \( u_\gamma = u_B \) this corresponds to maximum energies \( E_{p,\text{max}} = 10^6 \text{ TeV} \) and \( E_{e,\text{max}} = 4 \text{ TeV}. \) The assumption of \( K = 0.1 \) is certainly an overestimate for electrons which, owing to their much smaller Larmor radius, are in resonance with much smaller scales of the expected inverse-power-law plasma turbulence spectrum than protons. The ratio of cooling time scales for electrons and protons is given by

\[
\frac{t_e}{t_p} = \frac{1}{E_p} \frac{dE_p}{dt} \left( \frac{1}{E_e} \frac{dE_e}{dt} \right)^{-1} = \left( \frac{m_e}{m_p} \right)^3 \frac{\gamma_p f_p}{\gamma_e f_e}
\]

from which one can readily approximate the proton induced luminosity in terms of the electronic inverse-Compton and synchrotron luminosity

\[
L_p \approx \frac{u_p}{u_e} \frac{t_e}{t_p} L_e = \frac{u_p}{u_e} \left( \frac{m_e}{m_p} \right)^3 \frac{\gamma_p f_p}{\gamma_e f_e} L_e
\]

where \( u_p \) and \( u_e \) denote the energy densities in protons and electrons, respectively. To estimate the ratio of Lorentz factors relevant for the luminosities it is important to realize that the synchrotron luminosity is mainly due to electrons with \( t_e \leq t_{\text{dyn}} \) where \( t_{\text{dyn}} = r_{sh}/c \) denotes the dynamical time scale associated with the expansion of the shock front. The luminosity is not dominated by emission from the most energetic electrons, but increases only logarithmically above \( t_e = t_{\text{dyn}} \) corresponding to Lorentz factors \( \gamma_e \sim 10^2 \) (infrared break). With \( \gamma_{p,\text{max}} \sim 10^9 \) one obtains from Eq.(7) a maximum proton-induced luminosity of the order of

\[
L_{p,\text{max}} \approx \frac{u_p}{u_e} L_e
\]

Photoproduction by ultra-relativistic protons in a relativistic jet has been considered by a number of authors assuming different locations of the \( \gamma \)-ray emitting zone, either very close to the central black hole, at a distance of the order of the broad emission line region radius, or beyond the broad line region where the jet is dominated by its own synchrotron radiation field. Interestingly, the proton maximum energies and luminosities required to explain the blazar \( \gamma \)-rays conspire to produce the observed flux of ultra-high energy cosmic rays.

The bulk flow of relativistic particles can be distinguished as being either a cold beam or a hot beam. In the former case, the particles have zero kinetic energies in the frame co-moving with the bulk flow. The TeV \( \gamma \)-ray observations would then require cold beams with particle energies of at least several TeV. In the latter case, the bulk flow need only be moderately relativistic to accommodate for the superluminal motion and the absence of pair attenuation, whereas the co-moving frame energies are ultra-relativistic. Superluminal motion of radio knots suggests bulk Lorentz factors \( \Gamma \sim 10 \) (at the \( \sim 0.1 \text{ pc} \) scale) and observations of the synchrotron
turnovers indicate co-moving frame Lorentz factors of up to several tens of GeV. Cold beams could be generated through ordered electric fields close to the central object or electric drift fields arising at standing shock waves. Cold beams are expected to slow down reaching bulk Lorentz factors of $\Gamma \sim 10$ owing to Compton drag. Moreover, the same target radiation field which is assumed to be up-scattered to $\gamma$-ray energies would attenuate the $\gamma$-rays by pair production on a comparable time scale above photon energies of $m_e c^2$. An interesting idea is that cold sub-beams embedded in a larger scale jet could be produced at shocks in the winds of stars orbiting through the jet plasma. To explain the variability in Mrk421, one would, however, need an unexpected high density of mass-losing stars in the central stellar cluster. Since the Compton-drag on cold beams is difficult to avoid and the bulk Lorentz factors inferred from radio observations are much smaller than the Lorentz factors of the emitting particles, one needs in situ particle acceleration further downstream the jet as assumed in the hot beam models. Hot beam models with only one zone of emission in the jet (a ‘blob’) and external photons as the dominant target for inverse-Compton scattering (external Compton models: EC) have been published assuming that the blob is close to the nucleus at a distance of $(10^2 - 10^3) r_S$ or at the distance of the broad emission line region at $(10^3 - 10^4) r_S$. In the hadronic variant of this idea, protons are assumed as the primaries initiating synchrotron cascades by scattering external photons (E-PIC). In synchrotron-self-Compton models, the $\gamma$-rays originate in the jet where it is dominated by the internal synchrotron photons, i.e. presumably at distances of $> 10^4 r_S$. Again, there is a hadronic analogue, the proton-initiated synchrotron cascade model (PIC, denoted as S-PIC in Fig. 4). The closer the $\gamma$-ray emitting zone to the center, the lower the $\gamma$-ray energy which can be emitted without attenuation. The inhomogeneous EC models consider the emission of a Poynting flux/pair jet from close to the nucleus to the edge of the broad emission line region, the effect of this energy-dependent $\gamma$-photosphere is that with increasing photon energy, the $\gamma$-rays come from increasingly distant parts of the jet. Recently, it has been pointed out that the high density of pairs required in these models at $r < 10^2 r_S$ would lead to a bump in X-rays from inverse-Compton scattering of disk photons. Instead of a bump, blazars show a deep gap in X-rays. As can be seen from Fig. 1, all possible combinations of the basic assumptions have been investigated. In Sect. 2, the model predictions are confronted with observations. Section 3 concludes with a critical discussion of the models for high-energy emission from blazars.

2 Key observational results and model predictions

2.1 Fraction of $\gamma$-ray sources among blazars

A fraction of $\sim 10\%$ of all blazars have been detected in the EGRET pass-band 100 MeV – 10 GeV. The blazar fraction refers to those flat-spectrum radio sources which would have been above the EGRET flux sensitivity if the ratio between their $\gamma$-ray and 5 Ghz radio fluxes were at least as large as the lowest value for the EGRET detected blazars. An obvious explanation of the 10% would be flux variability which is, however, inconsistent with the 30% duty cycle of the strong EGRET detections. Intermittent behavior is suggested by interferometric radio observations which show months or years between the ejection of new radio knots, possibly associated with periods of $\gamma$-ray flaring and quiescence. Nevertheless, some quasi-stationary emission models make definite predictions about the $\gamma$-ray blazars representing a true subset of all blazars. EC models predict a stronger Doppler boosting of the $\gamma$-ray flux $\propto \delta^{4+2\alpha}$ compared with the radio-to-optical synchrotron flux which is boosted only by the factor $\delta^{3+\alpha}$. With $\alpha = 1$, the prominence of the $\gamma$-ray component increases $\propto \delta^2$ implying that the most pronounced $\gamma$-ray blazars must be the ones with the largest Doppler factors (smallest viewing angles or largest bulk Lorentz factors). This prediction can be tested experimentally with interferometric
radio observations. There are claims that, indeed, the strong EGRET sources have atypically high values of the Doppler factor \( \delta \), whereas there the Doppler factors of the EGRET sources among the S5 radio sources are normal for blazars. In the PIC model, the ratio between \( \gamma \)-ray and radio-to-optical luminosity depends on the proton-to-electron ratio and on the ratio of cooling time scales, see Eq. (5). There is no reason to believe that either one should be constant, it is rather plausible that the numbers vary with shock obliquity, Lorentz factor, and jet magnetization. Proton acceleration is likely to be limited due to the particle gyroradius \( r_L \) exceeding the shock radius of curvature \( r_{sh} \) rather than due to energy losses. If this is indeed the case, one obtains \( r_L \propto r_{sh} \propto r_j \) at the maximum energy with \( r_j \) denoting the jet radius. From eq.(7), the ratio of proton induced \( \gamma \)-ray and electronic synchro/Compton luminosity is then given by \( L_p/L_e \propto \gamma_{p,\text{max}} \propto r_j B \). Jet formation models give the scaling \( r_j \propto M_{bh} \) and \( B \propto r_{\text{edd}}^{1/2}M_{bh}^{-1/2} \) (from \( u_B = u_{\text{edd}} \)). The parameter \( r_{\text{edd}} = L/L_{\text{edd}} \) denotes the luminosity in units of the Eddington luminosity. Hence one obtains \( L_p/L_e \propto M_{bh}^{1/2}r_{\text{edd}}^{1/2} \). Thus, in the PIC model quasars, which are intrinsically more luminous than BL Lacs and therefore require larger \( M_{bh} \)'s or \( r_{\text{edd}} \)'s, are expected to be relatively more luminous in \( \gamma \)-rays than BL Lacs which is consistent with observations. The non-detected blazars would correspond to jets associated with sub-Eddington accretion flows.

### 2.2 Amplitude of \( \gamma \)-ray/radio luminosity ratio

The ratios between the observed \( \gamma \)-ray and radio luminosities range roughly between \( 10^2 \) and \( 10^4 \) (Fig. 2). If \( \gamma \)-ray blazars have a true distribution of \( \gamma \)/radio amplitudes larger than 100, so that only the 10% with the largest amplitudes show up above the EGRET sensitivity threshold, the observed blazar fraction could easily be explained. In the EC model, the amplitude distribution is triggered by the jet Doppler factor and with \( \delta = 1 - 10 \) the model predicts amplitudes between \( \delta^2 = 1 - 100 \). Maximum Lorentz factors somewhat larger than 10 would therefore be sufficient to explain the width of the amplitude distribution. As shown above, the PIC model requires that the product of black hole mass and Eddington ratio spans a range of more than \( 10^4 \) which is also necessary to explain the range of blazar bolometric luminosities. Whereas the EC and PIC models entail satisfactory explanations of the blazar fraction and the amplitude distribution, the SSC models are inconsistent with the observations of a few high-luminosity quasars such as 3C279 and PKS 0528-134 in which the \( \gamma \)-ray luminosity exceeds the radio-to-optical synchrotron luminosity by factors \( 10 - 100 \). This follows from re-writing the ratio of the singly scattered Compton luminosity to the synchrotron luminosity in terms of the Thomson optical depth \( \tau_T \) which yields \( L_{\text{SSC}}/L_{\text{syn}} \approx \tau_T \ln(\nu_e/\nu_b) \approx 5\tau_T \) for the typical synchrotron spectra with spectral index \( \alpha = 1 \) between frequencies \( \nu_b \) in the infrared and \( \nu_e \) in the ultraviolet. This does not say that the SSC mechanism is generally unimportant, it could still be the dominant process in the BL Lac objects where \( L_{\gamma} \approx L_{\text{syn}} \).

### 2.3 Spectrum

All models do rather well in fitting spectral data (for an example, see Fig. 3). However, the sharp MeV break seen in some of the spectra is reproduced by EC and SSC models only by the \textit{ad hoc} assumption of a break in the electron spectrum and it is difficult to find a physical process which could lead to this particular break. Coulomb losses must be negligible, otherwise the density of electrons is too large to comply with the weakness of the X-ray emission (absence of Sikora-bump). Inhomogeneous EC models can easily reproduce MeV breaks assuming steep gradients along the jet. In the PIC model, the high-energy emission is due to \textit{unsaturated} synchrotron cascades which, contrary to \textit{saturated} cascades, can produce very hard X-ray spectra depending on the slope of the target photon spectrum. However, \( \gamma \)-ray attenuation is required
to keep the $\gamma$-ray flux below Whipple limits. A natural source of the attenuating target photons is a heated dust torus. The PIC model predicts an average spectrum $\propto E^{-2}$ from MeV to TeV, and roughly $\propto E^{-3}$ above. The upper break is less certain, it depends on the range of distances in which proton cooling is important. In the PIC model, $\gamma$-ray emission is considered only from the part of the jet where the infrared target photons become optically thin. This is expected to be the most $\gamma$-ray luminous part of the jet.

2.4 Cut-off

Since the $\gamma$-ray spectra are broad featureless continua, the cut-off energy is of great diagnostic value. No cut-off is generally seen in the $\gamma$-ray spectra of blazars up to $\sim 10$ GeV above which the EGRET sensitivity drops rapidly. Generally, the flux level of the EGRET spectra extrapolated to air-Cerenkov energies exceeds the sensitivity of existing telescopes. Nevertheless, only 2(3) of the nearest blazars have been detected at TeV energies which is commonly ascribed to the attenuation of $\gamma$-rays due to pair production in the extragalactic infrared background. The large zenith angle observations of Mrk421 indicate that the spectrum extends at least to 5-8 TeV with no evidence for attenuation. A possible excess of $\gamma$-ray showers at still higher energies from the stacked source positions of the nearest blazars (including Mrk421) with redshifts $z \leq 0.07$ has been claimed on the basis of an advanced analysis of HEGRA array data. The significance of this excess has not yet been established unequivocally. Eqs.(4) and (5) show a quite general result regarding the maximum possible energy in leptonic and hadronic emission models. If the observed 5-8 TeV emission from Mrk421 is to be explained by any model in which the primaries are accelerated electrons, the electron Lorentz factors must reach at least $10^7$. The same electrons are assumed to produce the radio-to-soft-X-ray spectrum by synchrotron emission. With an observed turnover energy of $\epsilon \sim 300$ eV and the formula for the characteristic synchrotron energy $\epsilon \sim 10^{-8} B \gamma^2$ eV one obtains $B \sim 310^{-4}$ G. Eq.(5) implies that the magnetic field in the acceleration region must be $< 1$ G adopting (optimistically) $K = 0.1$ and $f_e = 2$ which is consistent with the above estimate. However, fields with a strength of $B \sim 10^{-4}$ G are found observationally in the hot spots of jets at the kiloparsec scale. This is at least $\sim 10^6$ times larger than the size of the $\gamma$-ray zone inferred from variability. Adiabatic flux compression to the scale of the $\gamma$-ray emitting zone yields $B$-fields somewhere in the range $0.1 - 100$ G. Taking into
account a Doppler factor $\delta \sim 10$ does not change these conclusions significantly. Therefore, the magnetic field values implied by SSC models fitted to $\sim 10$ TeV emission seem unrealistically low. An estimate similar to Eq.(5) yielding $\sim 10$ TeV as the maximum possible energy for leptonic models has been calculated assuming ordered electric fields. The leptonic limit is in marked contrast to the hadronic models which naturally produce $> 10$ TeV energies.

2.5 Variability

Doubling time scales of days to months seem to be common among strong EGRET sources. Considering the long integration times required to obtain 5-$\sigma$ detections the minimum variability time scales could also be shorter. Much shorter time scale variability has been discovered in Mrk421 at TeV energies taking advantage of the superior aperture of the air Cerenkov method. The shortest time scales expected for emission from blazar jets are of the order of $\Delta t \sim r_j/(c\delta)$ where the minimum jet radius can be estimated from asymptotic solutions of the equations for the radial structure of self-collimating hydromagnetic jets. This yields $r_j = 10\Gamma r_S = 3 \times 10^{15} \Gamma_{10} m_8$ cm where $\Gamma_{10} = \Gamma/10$ and $m_8 = M/10^8 M_\odot$ denote bulk Lorentz factor and the mass of the black hole, respectively, so that one obtains

$$\Delta t_{\text{min}} \sim \frac{10\Gamma r_S}{c\delta} \sim 5 \times 10^3 m_8 \, \text{s}$$  \hspace{1cm} (9)$$

assuming that blazars have favorably large Doppler factors $\delta \sim \Gamma$. In principle, one could further reduce this minimum time scale by another $\delta^{-1}$ factor if the jet opening angle exceeds $\sim 1/\Gamma$ or if the emission region is very thin and running through inhomogeneities. In spite of the short variability time scales, the pair creation optical depth of the emission region can be very small. The maximum optically thin energy for a spherical blob is given by $E \sim 3\delta^6 L_{44}^{-1} [e/\delta^2] \Delta t_4$ TeV where $L_{44}$ denotes the apparent luminosity in units of $10^{44}$ erg/s and $\Delta t_4$ the variability time scale in units of $10^4$ s. The low compactness is an essential requirement for the PIC model which would otherwise overproduce X-rays. In fact, the PIC model has predicted emission above TeV from the presence of X-ray gaps in the blazar spectra.
Figure 4: Tentative score chart (model explains observations naturally [**], with ad hoc assumptions [*], not at all [0]). Blazar emission above $\sim 10$ TeV would practically rule out the leptonic models, as indicated by [(0)].

### 2.6 Correlations

The claimed $\gamma$-ray/optical correlation is consistent with EC models, if the variations are due to a varying bulk Lorentz factor. In this case, one would expect the amplitude of the $\gamma$-ray variations to be larger than the synchrotron variations, as seems to be the case in 3C273. SSC models predict proportional variations in this case and quadratic ones, if the variations are due to a variable comoving frame maximum Lorentz factor. The latter is suggested by UV/X-ray observations of blazars. The PIC model predicts basically the same variability pattern as the SSC model (protons instead of electrons scattering off synchrotron photons). The only difference is that variations of the electron maximum energy do not necessarily imply the same variations of the proton maximum energies, if the maximum energies are determined by a subtle balance between acceleration, energy losses, and expansion. Thus, the PIC model is less predictive in this respect. The inhomogeneous EC models, in which the time scales for $\gamma$-ray variations increase with energy and in which the TeV and optical emission sites are not in the same part of the jet, are clearly inconsistent with the claimed correlations.

### 2.7 Warm dust $\gamma$-ray attenuation

As outlined in Sect. 1, the $\gamma$-ray emission models assuming external photons as the dominant target rely on a parametrization of the inner parsec of AGN as given by unified schemes. An element of the unified schemes which has more recently been recognized to be important is the dust torus heated by nuclear radiation feeding the accretion flow onto the black hole. The sublimation temperature of dust is $\sim 1700$ K and determines the inner edge of the torus to be at

$$r_{d} \sim 2 \times 10^{4} \left(\frac{L_{\text{edd}}}{m_{8}}\right)^{\frac{1}{2}}r_{S}$$

assuming a covering fraction of 0.5. This is roughly the same as the radius of the broad line region. The thermal NIR photons emitted from the warm dust torus absorb practically any $\gamma$-ray with energy above $\sim 300$ GeV emitted from $r < r_{d}$. On the basis of a straw person’s unified scheme, EC models are therefore ruled out as an explanation of TeV sources.
3 Discussion and conclusions

The results of Sect. 2 are summarized in Fig. 4. More refined models with more parameters could certainly improve some of the low scores, but some fundamental problems remain. The EC models have difficulties explaining the TeV emission due to the attenuating warm dust radiation field and the SSC models have difficulties explaining the enormous $\gamma$-ray luminosities of some quasars. The very attractive inhomogeneous EC models fail to explain $\gamma$-ray/optical correlations. The problems of the leptonic models could be ameliorated by assuming a transition from SSC to EC behavior when going from BL Lacertae objects to flat-spectrum radio quasars. Even if the emission properties can be explained by electron acceleration only, the absence of the Sikora X-ray bump is more in line with the energy transport in jets being dominated by protons rather than pairs and Poynting flux.

In any model, the observed short variability time scales observed in Mrk421 push the required acceleration times toward their limiting values allowed by diffusive shock acceleration and indicate that the size of the $\gamma$-ray emitting region is much smaller than its distance to the active nucleus. This is expected if the emission originates in the radiative downstream regions of shocks with a thickness of the order of the optical synchrotron cooling length.

Observations above 10 TeV are crucial for the discrimination between leptonic and hadronic models, but they are unfortunately hampered by the expected cosmic attenuation of $\gamma$-rays at these energies even for nearby blazars. The detection of Mrk421 at 5 TeV and the possible cumulative excess of HEGRA events from the nearest blazars are encouraging hints that the cosmic transparency is not exceedingly strong. Ultimately, observations with high-energy neutrino telescopes could bring us closer to an understanding of the puzzling nature of blazars and their relation to ultrahigh-energy cosmic rays.

Acknowledgments

Support by a European Training and Mobility of Researchers grant is greatly acknowledged.

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