Neutrino Oscillations and Blazars

Karl Mannheim

Universität-Sternwarte Göttingen, Geismarlandstraße 11, D-37083 Göttingen

Abstract

Three independent predictions follow from postulating the existence of protons co-accelerated with electrons in extragalactic jets (i) multi-TeV gamma ray emission from nearby blazars, (ii) extragalactic cosmic ray protons up to $\sim 10^{20}$ eV, and (iii) extragalactic neutrinos up to $\sim 5 \times 10^{18}$ eV. Recent gamma ray observations of Mrk 421 and Mrk 501 employing the air-Cerenkov technique are consistent with the predicted gamma ray spectrum, if one corrects for pair attenuation on the infrared background. Prediction (ii) is consistent with cosmic ray data, if one requires that jets are responsible for at least a sizable fraction of the extragalactic gamma ray background. With cubic kilometer neutrino telescopes, it will be possible to test (iii), although the muon event rates are rather low. Neutrino oscillations can increase the event rate by inducing tau-cascades removing the so-called Earth shadowing effect.

1 Introduction

In the early days after the discovery of extragalactic radio sources, it was a widely held belief that the relativistic electrons responsible for the observed synchrotron emission are secondary electrons from pp-interactions of accelerated protons on ambient gas (1; 2). Protons and ions were known to be the by far dominant species in the observed cosmic rays, and this was expected to be mirrored at their acceleration sites. Nevertheless, the picture was soon given up, since it would require enormous amounts of target matter in the jets which is inconsistent with plausible energetics and the non-observation of emission lines and bremsstrahlung. An electron-positron composition of the jets was also suggested from theory claiming that the plasma feeding radio jets should be due to pair production in the ergosphere of a maximally rotating black hole (3). The dielectric properties of radio jets inferred from observations of weak Faraday rotation and circular polarization in the jet of 3C279 seem to lend further support to a light composition (4). However, this picture also bears several fallacies.
Target matter does not have to be present to obtain efficient cooling of accelerated protons. Photo-production of secondary particles and synchrotron emission can become important, if the proton energy is high enough, since the cooling rate for these processes decreases with energy. In fact, in a statistical acceleration process in which there is enough time and space to balance acceleration energy gains against energy losses, it is an inevitable consequence that the protons reach ultrahigh energies (5; 6). Even if the original composition of the jet plasma were light, polluting baryons from the ambient medium would quickly take over most of the jet’s momentum, so that the acceleration mechanism must eventually tap baryonic kinetic energy. In fact, for gamma ray bursts, this is believed to be the crucial explanation for the fact that the burst energy is tapped only by shock fronts far away from the site of the original pair fireball (8). Therefore, it is the most natural assumption that the observed nonthermal emission is partly due to the accelerated electrons, and partly due to the accelerated protons (7). Inferences of the plasma composition based on measurements of polarization and Faraday rotation are based on the assumption that the electron distribution observed in the optically thin synchrotron regime traces down to lower energies which is known to lead to theoretical inconsistencies (9). Since the radiative properties are determined by the particles with the highest energies but the dielectric properties by those with the lowest energies, there is a general mismatch in the conclusions drawn from observations sensitive to either regime and one must be careful with claims about jet composition.

It may be a good advice not to be too narrow-minded when confronted with a new observational result such as multi-TeV emission from blazars and to include as many independent facts as possible in its interpretation. If the gamma rays were indeed primarily of a hadronic origin, there are a number of corollaries which allow to falsify the claim, whereas the arguments for a purely leptonic origin of the gamma rays boil down to some version of Ockham’s razor (“it is more economic to use the observed electrons to model the gamma ray emission”). I wonder whether this is enough to get around the symptomatic fact that there was no prediction of multi-TeV emission from leptonic models prior to the observations. Moreover, there are problems with leptonic models, such as the missing intrinsic curvature in the multi-TeV spectrum of Mrk 501 and the surprisingly low magnetic field values as was pointed out in ref. (10). Although the most recent HEGRA spectra of Mrk 501 (11) do show some curvature, the lower limits on the infrared background imply that the intrinsic spectrum must be rather flat or even up-turning (12).

One might as well argue that it is much more in the sense of Ockham’s razor (i.e. more economic), if one finds that the same sources which very likely produce most of the extragalactic gamma rays would at the same time produce cosmic rays at ultrahigh energies where it is difficult to find any other astrophysical source supplying enough power. There are two independent ob-
servations and only one model. According to Landau, a third independent fact is needed to consider a theoretical claim seriously. Here I consider the high-energy neutrino emission intimately connected with multi-TeV gamma rays from hadronic accelerators as the missing piece of information. To first elucidate the connection between extragalactic high-energy emissions in the framework of global energetics, Sect. 2 quantifies the non-thermal energy that may be released by active galactic nuclei and their jets integrated over their cosmic history. This qualifies extragalactic jets as possible sources of the ultrahigh energy cosmic rays and implies multi-TeV emission from the jets due to proton energy losses at their acceleration site. Section 3 discusses the predicted spectra from a simple quasi-stationary unsaturated synchrotron cascade emission model. Bearing on the assumption of a strong evolution of their luminosity density, the neutrino and cosmic ray spectra from extragalactic jets using the assumptions of the hadronic gamma ray emission model are computed in Sect. 4. Since the expected peak of the neutrino spectrum lies at energies in excess of 100 TeV at which the Earth becomes optically thick with respect to neutrino absorption, Sect. 5 extends the discussion by including the profound effects of neutrino oscillations.

2 Origins of extragalactic background radiation

Inspection of Fig. 1 shows an interesting pattern in the present-day energy density of the diffuse isotropic background radiation consisting of a sequence of bumps each with a strength that is decreasing with photon energy. The microwave bump is recognized as the signature of the big bang at the time of decoupling with its energy density given by the Stefan-Boltzmann law $u_{3K} = \sigma T^4$. The bump in the far-infrared is due to star formation in early galaxies, since part of the stellar light, which appears as the bump at visible wavelengths, is reprocessed by dust obscuring the star-forming regions. The energy density of the two bumps can be related to the present-day heavy element abundances. Heavy elements with present-day mass fraction $Z = 0.03$ were produced in early bursts of star formation by nucleosynthesis with radiative efficiency $\epsilon = 0.007$ yielding the present-day energy density

$$u_{\text{ns}} \sim \frac{\rho_* Z \epsilon c^2}{1 + z_f}$$  \hspace{1cm} (1)$$

where $\rho_*$ denotes the mass density of baryonic matter and $z_f$ the formation redshift corresponding to the era of maximum star formation. This is, of course, only a very rough approximation of the true star formation history, but good enough to set the scale for an argument pertaining to the global energetics. In particular, the ratio between the energy released by stars and by other
Fig. 1. Sketch of the present-day energy density of the extragalactic radiation background from radio waves to gamma rays.

sources with the same formation history is independent of its details. Let $\Omega_*$ denote the baryon density in terms of the critical density of the Universe and $h = H_0/100$ km s$^{-1}$ Mpc$^{-1}$ the dimensionless Hubble constant, then the energy density takes the value

$$u_{\text{ns}} \sim 6 \times 10^{-3} \left( \frac{\Omega_* h^2}{0.01} \right) \left( \frac{1 + z_f}{4} \right)^{-1} \text{eV cm}^{-3}$$

(2)

and should represent the energy density of the sum of the far-infrared and optical bumps. Probably all galaxies (except dwarfs) contain supermassive black holes in their centers which are actively accreting over a fraction of $t_{\text{agn}}/t_* \sim 10^{-2}$ of their lifetime implying that the electromagnetic radiation released by the accreting black holes amounts to

$$u_{\text{accr}} \sim \frac{\epsilon_{\text{accr}} M_{\text{bh}}}{Z \epsilon M_*} \frac{t_{\text{agn}}}{t_*} u_{\text{ns}} \sim 1.4 \times 10^{-4} \text{eV cm}^{-3}$$

(3)

adopting the accretion efficiency $\epsilon_{\text{accr}} = 0.1$ and the black hole mass fraction $M_{\text{bh}}/M_* = 0.005$ (13). Most of the accretion power emerges in the ultraviolet where the diffuse background is unobservable owing to photoelectric absorption by the neutral component of the interstellar medium. However, a fraction of $u_\gamma/u_{\text{bh}} \sim 20\%$ taken from the average quasar spectral energy distribution (14) shows up in hard X-rays producing the diffuse isotropic X-ray background bump with $u_\gamma \sim 2.8 \times 10^{-5}$ eV cm$^{-3}$ (15). Jets with non-thermal $\gamma$-ray emission show up only in the radio-loud fraction $\xi_{\text{rl}} \sim 20\%$ of all AGN and their
kinetic power roughly equals the accretion power (16). Hence one obtains for the energy density due to extragalactic jets

\[ u_j = \left( \frac{\xi_{rl}}{0.2} \right) u_{\text{acce}} \sim \left( \frac{\xi_{rl}}{0.2} \right) 2.8 \times 10^{-5} \text{ eV cm}^{-3}. \]  

(4)

This energy is released in relativistic particles, magnetic fields, and pdV thermodynamic work against the ambient medium into which the jets propagate. Adopting a radiative efficiency of \( \xi_{\text{rad}} = 10\% \) for the jets, the gamma ray (cosmic ray, neutrino) energy released by the jets can amount to a maximum present-day energy density of

\[ u_{\gamma} \sim \xi_{\text{rad}} u_j \sim 2.8 \times 10^{-6} \left( \frac{\xi_{\text{rad}}}{0.1} \right) \left( \frac{\xi_{rl}}{0.2} \right) \text{ eV cm}^{-3} \]  

(5)

which comes remarkably close to the energy density \( 3.2 \times 10^{-6} \text{ eV cm}^{-3} \) of the extragalactic gamma ray background observed between 100 MeV and 30 GeV\(^1\) using the spectrum given in ref. (17). Note that this is consistent with having a particle acceleration efficiency in radio jets which is of the same order of magnitude as the 13% efficiency required for supernova remnants to produce the Galactic cosmic rays.

Protons can achieve a high radiative efficiency due to photo-production of secondary particles or synchrotron emission only if they reach ultrahigh energies. This can be seen most easily for synchrotron radiation in which case the proton Lorentz factor must be larger than the electron Lorentz factor by \( (m_p/m_e)^3 \) to produce the same cooling rate. Particles with energies exceeding \( 6 \times 10^{18} \text{ eV} \) may seem outrageously exotic to many astrophysicists, but they are actually observed in the local cosmic ray spectrum. These particles cannot be confined by the Milky Way, but nevertheless show a near-isotropic sky distribution. Furthermore, the local cosmic ray spectrum flattens above \( 6 \times 10^{18} \text{ eV} \) indicating a separate extragalactic source population. It will be argued in Sect.4 that only an extragalactic source population as strong as the one supplying the diffuse isotropic gamma rays can be considered for their origin. Before highlighting these arguments, it is shown in the next section that protons at such high energies produce interesting gamma ray spectra owing to the photo-production of secondaries.

\(^1\) Note that the flux in the gamma ray background observed by CGRO is close to the bolometric gamma ray flux, since pair attenuation and cascading must lead to a turnover of the background spectrum above 20 – 50 GeV for extragalactic source populations (18; 19)
3 Proton blazar predictions and observed multi-TeV spectra

A large number of emission models for radio jets based on a shock-in-jet scenario exist and have been shown to explain most of the low-frequency jet phenomenology using a number of parameters such as jet kinetic energy, magnetic field gradient, opening angle of the flow channel, etc. within plausible ranges. It is straightforward to include relativistic protons in such models assuming they have a spectrum with the same slope but different maximum and minimum energies (due to different energy losses, gyro-resonant thresholds, and Larmor radii). Among the interesting consequences of the protons are (i) a higher nonthermal pressure and (ii) more gamma ray flux (adding to the Compton flux from the accelerated electrons). The equipartition magnetic field strength increases according to $B \propto \kappa^{2/7}$ where $\kappa = u_p/u_e$ denotes the ratio between the energy density in relativistic protons and electrons, respectively, and this may help to alleviate some problems for pair jets such as the observed pressure support of the radio lobes in NGC 1275 against the surrounding hot intrachannel medium of the Perseus cluster (20).

In terms of simplicity and predictive power, the original Blandford & Königl conical jet model (21) is useful and has been investigated for the radiative signatures of the protons (7). The model describes the stationary emission from a conical section of a free relativistic jet and is therefore of limited applicability to non-stationary features in the observed spectra. The relativistic particle and magnetic energy density decreases as $\propto r^{-2}$ along the jet, i.e. the jet is isothermal. The emitting conical section of the jet may be thought of as the unresolved superposition of a number of shocks traveling down the jet, and shock acceleration keeps the nonthermal energy constant. Such a jet emits a flat radio spectrum up to the frequency where the spectrum steepens by one power due to the energy losses, typically in the submm-infrared regime. The flux at this break frequency is dominated by the jet cone near its apex. The threshold frequency $\nu_{\text{th}}$ for the production of pions in head-on collisions between photons and protons with Lorentz factor $\gamma_p$ is given by

$$\nu_{\text{th}} \approx 10^{12} \left( \frac{\gamma_p}{10^{11}} \right)^{-1} \text{ Hz}$$

showing that the region of maximum surface brightness temperature is most important for the cooling of protons. Owing to electromagnetic cascading the electromagnetic power injected into the jet plasma by the cooling baryons is redistributed smoothly over the X-ray and gamma ray bands. Therefore, the emission component with the largest energy flux dominates the entire high-frequency spectrum and proton-initiated cascade spectra have been computed only for this zone. An integration along the jet axis (which is necessary to obtain the flat radio spectrum) would only lead to marginal corrections in the
gamma ray regime. The geometry is depicted in Fig. 2 together with a sketch of the emission components from the various scales. Due to the small size of the region dominating the gamma ray energy flux compared with the total volume of the conical jet, traveling shocks would make the gamma ray emission much more susceptible to flux variability than the radio-infrared emission in qualitative agreement with the observations. As long as the perturbation time scale is larger than the proton acceleration time scale, the emission spectra can still be computed as quasi-stationary spectra, and it is an open theoretical challenge to solve for the spectra in the general time-dependent case. An interesting time-dependent solution exists for a simplified version of Compton-scattering dominated proton-initiated cascades (22). Using the Doppler factor $\delta$ to convert between comoving and observer’s frame, the proton acceleration time scale assuming Bohm diffusion is given by

$$t_{\text{acc}} \simeq \frac{r_g}{\delta c} = \frac{\gamma_p m_p c}{\delta eB} \simeq 3.5 \times 10^4 \left( \frac{\gamma_p}{10^{11}} \right) \left( \frac{B}{30 \text{ G}} \right)^{-1} \left( \frac{\delta}{10} \right)^{-1} \text{s}$$

(7)

in comfortable agreement with some of the observed TeV flux variation time scales. The comoving frame gyro-radius of the protons

$$r_g \simeq 10^{16} \left( \frac{B}{30 \text{ G}} \right)^{-1} \left( \frac{\gamma_p}{10^{11}} \right) \text{ cm}$$

(8)

satisfies the constraint $r_g \leq r_j$ if the jet radius is the lightcylinder radius of an MHD jet from a black hole of mass $M$ and Schwarzschild radius $r_S$ in which case $r_j \simeq 100r_S \simeq 3 \times 10^{16}(M/10^9 M_\odot) \text{ cm}$. For time scales longer than the proton acceleration time scale, correlated flux variations from hard X-rays to TeV gamma rays are expected as a typical phenomenon (within the model assumptions). If the hard X-ray emission or the gamma ray emission in the EGRET band is dominated by emission from the accelerated electrons, the TeV variability can be different. This case would argue for a higher ratio of the photon to magnetic energy density $u_\gamma/u_B \sim 1$ than in the generally assumed case $u_\gamma/u_B < 1$ in the proton blazar model. Note also that variability on shorter time scales must be expected under realistic conditions, e.g. due to the presence of inhomogeneities along the jet. These variations can occur on time scales down to the cooling time scale of the cascade electrons, and require the solution of the time-dependent cascade equations. The short-term variability behavior of the cascades is very complicated owing to the pair production threshold varying with gamma ray energy.

The TeV detections of nearby blazars confirm the prediction of the proton blazar model that the relativistic jets should be optically thin to gamma ray emission below $\sim 1$ TeV. This means that the conversion of injected gamma rays into pairs and vice versa becomes unimportant below TeV (unsaturated
Fig. 2. Conical geometry for the relativistic jet with Lorentz factor $\gamma_j$ and opening angle $\Phi \sim 1/2\gamma_j$ assumed in the proton blazar model. Note that the total proton-initiated cascade emission from the cone is dominated by the emission from the region of highest surface brightness temperature in the submm-infrared regime at $r = r_b$ and is therefore more susceptible to variations due to traveling shocks (at position $r_s$ with velocity $\beta_s$). The sketch of the spectral energy distribution indicates the flux contributions from various scales $r$ in the jet. An additional effect increasing the gamma ray flux from the region of highest surface brightness temperature is indicated by the parameter $\xi$ which is proportional to the proton maximum energy and which is expected to decrease with $r$ due to the nonlinear development of the shock structure.

cascades). Emission above $\sim 1$ TeV is expected to be optically thick, but nevertheless of approximate power law shape. Synchrotron cooling is assumed to be the dominant process replenishing the gamma rays from the pairs. For the entire parameter space, synchrotron emission remains non-relativistic so that the characteristic synchrotron photon energy is much less than that of the radiating electrons assuring rapid convergence of the cascade equations (which can be brought into the form of a Volterra integral equation of the second kind) by Banach’s fixed point theorem. The shape of the multi-TeV spectrum follows from very simple considerations. It is assumed that the protons have a differential distribution $dN/dE \propto E^{-s_p}$. The electron distribution has the same slope in the optically thin range, but in the energy range responsible for producing the target photons for the protons their spectrum is steeper by one power $s_e = s_p + 1$ owing to energy losses. The electrons thus produce a synchrotron flux density spectrum $S_\nu \propto \nu^{-\alpha}$ with spectral index $\alpha = s_p/2$. In the original papers (7) it was assumed that $s_p = 2$ and correspondingly $\alpha = 1$ which is the non-relativistic result from 1st order Fermi acceleration at strong shocks in the test-particle approximation. A flatter value $s_p = 3/2$ corresponding to $\alpha = 3/4$ may be more appropriate for strong shocks in the general case (23). The cascades are initiated by gamma rays from the decay of the neutral pions at ultrahigh energies. The slope of the differential injection spectrum of the gamma rays is given by $\alpha$, but steepens due to pair creation
on the synchrotron target characterized by the optical depth $\tau(E) \propto E^\alpha$. The steepening can be described by the energy-dependent escape probability $P_{\text{esc}} = 1 - \exp[-\tau(E)]/\tau(E) \rightarrow \tau(E)^{-1} \propto E^{-\alpha}$ for $\tau \gg 1$, i.e. a steepening of the injection spectrum by $\alpha$. Hence, the stationary injection spectrum has the slope $s_{\gamma,1} = 2\alpha$. The next step in the cascade development involves the creation of pairs which have a stationary distribution with the same slope $2\alpha$ producing the second generation of gamma rays. Since generally these gamma rays still lie in the optically thick energy range, the stationary gamma ray distribution has the slope $s_{\gamma,2} = 2\alpha + 0.5$. The same is true for the new generation of pairs produced by these gamma rays, and their synchrotron gamma rays are mostly emitted at optically thin energies where their spectrum has the slope $s_{\gamma,3} = \alpha + 0.75$ (in the optically thick range the slope is $2\alpha + 0.75$). Thus the predicted multi-TeV slope is bracketed by $2\alpha + 0.5$ and $2\alpha + 0.75$. For $\alpha = 1$, the corresponding range is $2.5 - 2.75$ and for $\alpha = 0.75$ it is $2.0 - 2.25$ which is in reasonable agreement with the observations of Mrk 421 and Mrk 501 (11) corrected for the expected intergalactic gamma ray attenuation (12). The model spectrum fitted to lower frequency data as published prior to the 1997 HEGRA multi-TeV observations agrees remarkably well with the measurements (10). The shape of the multi-TeV spectrum is not sensitive to changes in the maximum energy and can remain constant under large-amplitude changes of the flux associated with changes in the maximum energy.

4 Neutrino and cosmic ray predictions

The photo-production of charged pions leads to the emission of neutrons and neutrinos. Neutrons associated with the production of $\pi^+$ have no efficient coupling with the magnetized plasma in the jet and therefore escape ballistically. The neutrons decay to protons after a propagation length $l_n = (\gamma_n/10^{11})$ Mpc, and such extragalactic cosmic rays suffer energy losses traversing the microwave background (25). At an observed energy of $10^{19}$ eV, the energy-loss distance is $\lambda_p \sim 1$ Gpc owing to pair production. This distance corresponds to a redshift $z_p$ determined by $\lambda_p = (c/H_0) \int_0^{z_p} dz/[(1 + z)E_{\text{JP}}(z)]$ where $E_{\text{JP}}(z) = [\Omega(1 + z)^3 + \Omega_R(1 + z)^2 + \Omega_\Lambda]^{1/2}$ with $\Omega + \Omega_R + \Omega_\Lambda = 1$. Almost independent on cosmology, the resulting value for $z_p$ is given by $z_p = h_{50}/(6 - h_{50}) \simeq 0.2 h_{50}$ where $h_{50} = H_0/50$ km s$^{-1}$ Mpc$^{-1}$. Therefore, when computing the contribution of extragalactic sources to the observed cosmic ray flux above $10^{19}$ eV, only sources with $z \leq z_p$ must be considered. Assuming further that extragalactic sources of cosmic rays and neutrinos are homogeneously distributed with a monochromatic luminosity density $\Psi(z) \propto (1 + z)^{3+k}$ where $k \sim 3$ for AGN (24), their contribution to the energy
density of a present-day diffuse isotropic background is given by

\[ u(0) = \int_0^{z_m} \Psi(z)(1+z)^{-4} \frac{dl}{c dz} dz = \frac{\Psi(0)}{H_0} \int_0^{z_m} (1+z)^k dz \]

where \( z_m = 2 \) denotes the redshift of maximum luminosity density. The factor \( (1+z)^{-4} \) accounts for the expansion of space and the redshift of energy. For a simple analytical estimate of the effect of energy losses on the proton energy density at \( 10^{19} \) eV, we collect only protons from sources out to the horizon redshift \( z_p \approx 0.2 \) for \( 10^{19} \) eV protons, whereas neutrinos are collected from sources out to the redshift of their maximum luminosity density \( z_m \). This yields the energy density ratio for neutrinos at an observed energy of \( \sim 5 \times 10^{17} \) eV and protons at \( 10^{19} \) eV

\[ \frac{u_\nu(0)}{u_p(0)} = \frac{\xi \int_0^{z_m} (1+z)^{k-2} / E_{JP}(z) dz}{\int_0^{z_p} (1+z)^{k-2} / E_{JP}(z) dz} \approx 2 - 3 \]

using \( \xi \approx 0.3 \) from decay and interaction kinematics, and considering an open Universe with \( E_{JP}(z) = (1+z) \) and a closed one with \( E_{JP}(z) = (1+z)^{3/2} \). Fig. 3 shows the exact propagated proton and neutrino spectra for \( \Omega = 1 \) from a full Monte-Carlo simulation employing the matrix doubling method of Protheroe & Johnson (26). The assumed neutron spectrum was \( dN_n/dE_n \propto E_n^{-1} \) (corresponding to \( \alpha = 1 \) in the previous section) up to \( 10^{18} \) eV and \( dN_n/dE_n \propto E_n^{-2} \exp(-E_n/E_{cut}) \) above. The steepening reflects the fact that the maximum energy may vary from source to source. The muon neutrino spectra follow the same shape, but they are shifted according to a simplified treatment of pion decay and production kinematics. A more accurate treatment yields small corrections (29). The neutron spectrum was normalized to the cosmic ray data yielding a neutrino spectrum consistent with model A from the original work (27). The associated gamma ray flux \( F_\gamma \approx 2 F_\nu \ln[100] \approx 2 \times 10^{-6} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) corresponds to a sizable fraction of the observed gamma ray background flux\(^2\). The neutrino flux is consistent with the bound given in ref. (28), although it is possible to have extragalactic neutrino sources of higher neutrino fluxes without violating the observed cosmic ray data as a bound (29). One could easily construct such models which produce the entire gamma ray background on the same rationale (29).

\(^2\) A recent paper by Waxman and Bahcall (28) refers to the neutrino flux from model B in the original work which was given only to demonstrate that hadronic jets can not produce a diffuse gamma ray background with an MeV bump (as measured by Apollo and which is now known to be absent from a COMPTEL analysis) without over-producing cosmic rays at highest energies.
5 Neutrino oscillations and event rates

The neutrino flux shown in Fig. 3 corresponds to a very low muon event rate even in a detector with an effective area of 1 km$^2$ ($\sim 1$ event per year and per steradian above 100 TeV). This event rate is a very conservative estimate, since there must be additional neutrino production due to pp-interactions of escaping nucleons diffusing through the host galaxies and galaxy clusters. The neutrino flux could also be increased by increasing the number of extragalactic jet sources with proton maximum energies well below $10^{19}$ eV (29). As a matter of fact, such a model ramification is required if one wants to explain the entire diffuse gamma ray background by hadronic photo-production sources.

At this point the discovery of neutrino mass announced by the Super-Kamiokande collaboration (30) changes the situation in a major way. A deficit of atmospheric muon neutrinos was observed with Super-Kamiokande at large zenith angles with the most likely explanation being a full-amplitude oscillation of muon flavor eigenstates to tauon flavor eigenstates across the Earth atGeV energies. The transition probability $P(\nu_\mu \to \nu_\tau)$ is a function of distance and energy $L/E$, i.e.

$$P(\nu_\mu \to \nu_\tau) \approx \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2}{10^{-3} \text{eV}^2} \frac{L}{10^4 \text{km}} \frac{L}{E} \text{GeV} \right) \tag{11}$$

where the mixing angle $\theta$ specifies the mixing amplitude $\sin^2(2\theta) > 0.82$. The
missing piece of information about the neutrino oscillations is the appearance of tau leptons to which Super-Kamiokande is not sensitive. A long-baseline experiment using muon neutrinos from a laboratory beam is extremely difficult if not impossible with existing laboratories, since one must establish a very large distance and a high energy to reach the tau mass shell at $m_\tau = 1.784$ GeV. The beam luminosity decreases rapidly with energy and distance which poses an irreducible problem. However, an astrophysical beam of muon neutrinos, such as the one proposed in this paper and for which the multi-TeV observations give us somewhat more confidence that they really exist, is ideally suited for this type of experiment, since both L and E obtain “astronomically large” values. Hence it follows that very likely astronomical high-energy neutrino sources such as extragalactic radio jets will help to solve a major puzzle in elementary particle physics.

There is another effect associated with neutrino oscillations which alleviates the problem with the low muon event rate of the predicted flux. To see this, one must realize that the solid angle for the detection of high-energy muon neutrinos becomes very narrow at energies in excess of $\sim 100$ TeV, since the Earth becomes optically thick to muon neutrinos above this energy (the weak interaction cross section depends on energy). This is called the Earth shadowing effect (31). Below 100 TeV the atmospheric background of neutrinos is too strong for the discovery of the rare events due to extragalactic neutrinos, unless the angular resolution of the neutrino telescopes is very good. Actually, the atmospheric background is comparable to the predicted astronomical background at around 100 TeV. Therefore one is confronted with the problem of a too small solid angle for events above 100 TeV and a too low rate below 100 TeV. If the neutrino oscillation hypothesis is correct, the extragalactic muon neutrino beam is fully mixed with tau neutrinos at Earth. Tau leptons produced by charged-current interactions inside the Earth decay before further interacting. Since the Earth is also opaque to tau neutrinos above $\sim 100$ TeV, all the tau neutrinos entering on the one side with energies above 100 TeV emerge on the other side with energies of around 100 TeV (32) obliterating the Earth-shadowing effect. In the proton blazar model with $\alpha = 1$, the number density of neutrinos above 100 TeV remains constant up to roughly $10^5$ TeV implying an increase in the contained event rate by a factor

$$
\xi_\tau = \frac{1}{2} \int_{10^2}^{10^5} \frac{dx}{x} = \ln \left[\frac{10^5}{10^2}\right] \simeq 3.5
$$

(12)

where the factor $\frac{1}{2}$ is for the mixing between muon and tauon neutrinos ($\frac{1}{3}$ would be appropriate for further mixing with electron neutrinos). The neutrinos from extragalactic radio sources can therefore be expected to produce more events than the atmosphere at around 100 TeV. Some of these events are not muon events, but direct tauon events. Owing to tauon decay, the tauon
tracks are very short \( l_\tau = 50 (E_\tau / 100 \text{ TeV}) \) cm and the main signature is the electromagnetic cascade from tau decay. Horizontal events can be of higher energy, producing the famous double-bang events with the first bang indicating the charged-current tauon production event and the second its decay. Thus, the glass is half-full.

6 Discussion and summary

The multi-TeV spectra from nearby blazars predicted on the basis of the proton blazar model are in accord with the observations if the effect of pair attenuation due to the extragalactic infrared background is taken into account. Variability patterns are similar to those in synchrotron-self-Compton models, but more complex, since variations of the target photon flux fold into the cascade development in a non-linear manner. Short time scale variability is likely to reflect the passage of shocks through inhomogeneities and correspond to cooling time scale variations. If the cosmic ray flux emitted by hadronic accelerators is enough to explain the observed cosmic rays above \( 10^{19} \text{ eV} \), the associated gamma ray power from these sources is enough to produce at least a sizable fraction of the observed extragalactic gamma ray background. The gamma ray power is larger than that in cosmic rays, since the cosmic rays lose energy traversing the low-energy background radiation fields and most sources have high redshifts. Strong evolution of their luminosity density would rule out GRBs as possible sources of the highest energy cosmic rays, since their cumulative gamma ray flux is far below the extragalactic gamma ray flux. Although the expected muon event rate in neutrino telescopes is low, neutrino oscillations lead to tau cascades canceling the Earth shadowing effect thereby increasing the detection probability.

References

[1] G.R. Burbidge, Astrophys. J. 124 (1956) 416.
[2] G.C. Perola, Astron. & Astrophys. 3 (1969) 481.
[3] R.D. Blandford, R.L. Znajek, Mon. Not. Roy. Astr. Soc. 179 (1977) 433.
[4] J.F.C. Wardle, et al., Nature 395 (1998) 457.
[5] P.L. Biermann, P.A. Strittmatter, Astrophys. J. 322 (1987) 643.
[6] M. Sikora, et al., Astrophys. J. 320 (1987) L81.
[7] K. Mannheim, W. Krülls, P.L. Biermann, Astron. & Astrophys. 222 (1991) 222, K. Mannheim, P.L. Biermann, Astro. & Astrophys. 333 (1992) L21, K. Mannheim, Astron. & Astrophys. 269 (1993) 67.
[8] P. Mészáros, M.J. Rees, Astrophys. J. 405 (1993) 278.
[9] R. McCray, *Astrophys. J.* **156** (1969) 329.
[10] K. Mannheim, *Science* **279** (1998) 684.
[11] A. Konolpenko, et al. (HEGRA Collaboration), this volume
[12] O.C. de Jager, E. Dwek, *Astropart. Phys.* (1999), submitted; F.W. Stecker, O.C. de Jager, *Astron. & Astrophys.* **334** (1998) L85.
[13] M.J. Rees, J. Silk, *Astron. & Astrophys.* (1998) **331**, L1.
[14] D.B. Sanders, et al., *Astrophys. J.* **347** (1989) 29.
[15] D.E. Gruber, *The X-ray Background*, eds. X. Barcons and A.C. Fabian, Cambridge U.P. (1992) p. 44.
[16] S. Rawlings, S. Saunders, *Nature* **349** (1991) 138.
[17] P. Sreekumar, F.W. Stecker, S.C. Kappadath, in: *Proceedings of the Fourth Compton Symposium*, eds. Charles D. Dermer, Mark S. Strickman, and James D. Kurfess, Williamsburg, VA, April 1997: AIP Conference Proceedings **410** (1998) p. 344.
[18] P. Madau, E.S. Phinney, *Astrophys. J.* **456** (1996) 124.
[19] M.H. Salamon, F.W. Stecker, *Astrophys. J.* **493** (1998) 547.
[20] H. Böhringer, W. Voges, A.C. Fabian, A.C. Edge, D.M. Neumann, *Month. Not. Roy. Astr. Soc.* **264** (1993) L25.
[21] R.D. Blandford, A. Königl, *Astrophys. J.* **232** (1979) 34.
[22] A. Mastichiadis, J. Kirk, *Astron. Astrophys.* **295** (1995) 613.
[23] M.A. Malkov, *Astrophys. J.* **511** (1999) L53.
[24] B. J. Boyle and R. J. Terlevich, *Mon. Not. Roy. Astro. Soc.* **293** (1998) L49.
[25] J. P. Rachen and P. L. Biermann, *Astron. & Astrophys.* **272** (1993) 161.
[26] R. J. Protheroe and P. A. Johnson, *Astropart. Phys.* **4** (1996) 253.
[27] K. Mannheim, *Astropart. Phys.* **3** (1995) 295.
[28] E. Waxman, J. Bahcall, *Phys. Rev. D* (1999) accepted.
[29] K. Mannheim, R.J. Protheroe, J.P. Rachen, *Phys. Rev. D.* (1999) submitted; F.W. Stecker, M.H. Salamon; *Space Sci. Rev.* **75** (1996) 341.
[30] Y. Fukuda, et al. (Super-Kamiokande Collaboration), *Phys. Rev. Lett.* **81** (1998) 1562.
[31] R. Gandhi, C. Quigg, M. H. Reno, and I. Sarcevic, *Astropart. Phys.* **5** (1996) 81.
[32] F. Halzen, D. Saltzberg, *Phys. Rev. D.* **81** (1998) 4305.