ABSTRACT

The article gives a brief overview, aimed at nonspecialists, about the goals and selected recent results of the detection of very-high energy $\gamma$-rays (energies above 100 GeV) with ground based detectors. The stress is on the physics questions, especially the origin of Galactic Cosmic Rays and the emission of TeV $\gamma$-radiation from active galaxies. Moreover some particle-physics questions which are addressed in this area are discussed.

1 Introduction: Very-high energy $\gamma$-rays and nonthermal processes in the universe

1.1 The nonthermal universe

The general aim of “very-high energy” (“VHE”, defined as $\gamma$ rays with energies from about 20 GeV up to about 50 TeV) $\gamma$-ray astrophysics is to explore the “nonthermal particles in the universe”. This is a designation for those cosmic particles that have been accelerated to energies at which they are no longer in thermal equilibrium with their surroundings, and for the radiation fields they produce. Discovered at the beginning of this century, Galactic cosmic rays constitute the most striking (but by no means only) evidence for nonthermal processes. They are observed near earth as an intense, nearly isotropic, flux of mainly protons and other nuclei with energies ranging from about 100 MeV to at least a few times $10^{20}$ eV. Electrons are a minor component (their intensity, at about 50 GeV energy, is only 1% of the hadronic flux). The hadronic energy spectrum is displayed in fig.1.
The total number of cosmic-ray particles, compared to thermal interstellar particles, is very small. Their total energy density, however, (about 0.5 eV/cm³ near earth) is comparable to other constituents of our Galaxy like e.g. interstellar magnetic fields and turbulent motion in the interstellar medium. Nonthermal particles are therefore likely to play an important role in the general dynamics of clusters of galaxies, our Galaxy and the objects which accelerate particles.

The basic questions for an understanding of the nonthermal universe are: Where, and with what mechanisms are particles accelerated in the universe? While there are experimental clues concerning the first question for electrons (from radio astronomy, X-ray and VHE γ-rays, to be discussed below) there is as yet scant unambiguous experimental evidence as to the origin of nonthermal hadrons, which seem to dominate the total energy density, at least in in the special case of Galactic cosmic rays. As an example for our lack of knowledge: for the energies shown in fig.1 (> 100 GeV/nucleus) there is no direct experimental evidence whatsoever about the local density of hadronic cosmic rays anywhere in the universe except near earth.

A mechanism that is very likely to play an important role in the acceleration, is the “first order Fermi mechanism” \[^{1}\,^{2}]. When macroscopic amounts of matter are ejected into interstellar space with velocities larger than the sound speed in the ambient medium, a shock wave forms. Reflected by inhomogeneities in the ambient magnetic fields, charged particles then have a certain probability to repeatedly cross the shock front and gain energy each time they do so. Extensive analytical and Monte Carlo studies have shown that this is a plausible mechanism to convert a nonnegligible part of the kinetic energy of the shock front into the energy of nonthermal particles. This mechanism predicts energy spectra obeying power laws with indices near \(\alpha=-2\) which is in agreement with observed spectra when additional mechanisms affecting the spectral form (e.g. energy-loss and

---

**Figure 1:** Energy spectrum of hadronic cosmic rays with energies > 300 GeV. The flux measurements from various experiments (below about 100 TeV from direct balloon and satellite data, above 1000 TeV from ground-based arrays) are plotted against the differential flux, multiplied by energy\(^{2.75}\) to remove the very fast power law decrease in intensity. Within the errors the spectrum displays a power law behaviour with three different indices below and above the “knee” (at about \(2 \cdot 10^{15}\) eV) and above the “ankle” at about \(3 \cdot 10^{18}\) eV. For a detailed explanation of the symbols see Wiebel.\[^{3}\].
propagation effects) are taken into account.
Theory is not yet able to a priori predict the hadron to electron intensity ratio, however \(2\).
The ambiguity in this crucial parameter, perhaps the most important single roadblock to a better understanding of the nonthermal universe, will reappear the discussion of VHE \(\gamma\)-ray sources below.

1.2 Ground based VHE \(\gamma\) astronomy

The currently dominating technique to measure cosmic \(\gamma\)-ray photons with energies from about 200 GeV to about 20 TeV uses Čerenkov telescopes. The primary gamma ray develops an electromagnetic cascade in the earth’s atmosphere which emits Čerenkov light. This light is detected in an optical telescope with typical mirror areas from about 5 to 70 m\(^2\). The Čerenkov light is emitted over an area of about 20000 m\(^2\) and each telescope situated whithin this “light pool” can detect the shower. This large detection area allows to reach good counting statistics: E.g. the Whipple collaboration detected in one observing season (spring ’96) about 5000 photons from the active galaxy Mkn 421 above 300 GeV \(4\). Until the end of the 1980s achievable sensitivities were seriously degraded by the fact that the hadronic showers from Galactic cosmic-rays produce a background which, even for the strongest sources, is about a factor 100 higher than the signal from photons. The imaging technique, pioneered by the Whipple collaboration \(5\) allows to reduce this background. A picture of the shower is registered in an array of fast photomultipliers in the image plane of the telescope that detect the few nanosecond long Čerenkov pulses. This technique is still in a state of evolution, the most advanced camera, presently in operation by the French CAT collaboration \(6\) has 546 pixels. Another crucial technological advance for Čerenkov telescopes, mostly advanced by the HEGRA collaboration, is the exploitation of stereo imaging \(7\). The same shower is viewed by several telescopes in coincidence and its full three dimensional structure can be reconstructed. Besides advantages like a better energy and angular resolution, the measurement of shower parameters is overdetermined and thus allows important consistency checks of the technique. The capabilites of existing detectors and planned future arrays of Čerenkov devices is illustrated in fig.\(2\).

1.3 The astrophysical production of VHE \(\gamma\)-rays

Nonthermal particles produce \(\gamma\)-rays in the interaction with ambient matter and radiation fields. As opposed to the particles themselves, which are charged and therefore isotropized in Galactic magnetic fields, \(\gamma\)-rays point back to the site of their production. At an acceleration site the density of nonthermal particles - and therefore the \(\gamma\)-ray emissivity - is expected to be high. The detection of VHE \(\gamma\)-ray sources thus yields clues about cosmic sites where particles are accelerated to energies of about 100 GeV and above. The two most important \(\gamma\)-ray production mechanisms for particles interacting with ambient matter (normally mostly hydrogen (H) are):
Figure 2: Sensitivities of various existing and planned detectors (adapted from VERITAS proposal), for high and very-high energy gamma rays for various energies (full lines) or at the energy threshold (big dot). A total measuring time of 50 hours was assumed for devices with a small field of view and 1 year for devices with a field of view of 1 steradian or larger (these are: satellites: EGRET (existing) and GLAST (planned) and the array MILAGRO (under construction)). WHIPPLE and HEGRA are existing telescopes, VERITAS and MAGIC proposed large future devices; HESS, another multi-telescope proposal, is expected to reach similar sensitivities as VERITAS. CELESTE, STACEE, and GRAAL are detectors which are currently being set up using the large mirror areas at solar power plants. The dotted line gives the extrapolation of a typical VHE source spectrum from GeV to VHE energies (active galaxy Mkn 421). The arrows indicate the intensity of this source during various viewing periods (“VP”) of the EGRET satellite.

1. for electrons: relativistic Bremsstrahlung \( (e + H \rightarrow e + H + \gamma) \)

The energy loss \( \delta E \) of this mechanism for electrons with an energy \( E_e \) in “astronomical units” (\( \rho \) is the ambient interstellar number density):

\[
\frac{\delta E}{\text{Lightyear}} \approx 25 \text{keV} \cdot \frac{E_e}{\text{TeV}} \cdot \left( \frac{\rho}{1/\text{cm}^3} \right)
\]

One obtains for the typical energy \( \gamma \)-ray energy \( E_\gamma \) produced by an electron of energy \( E_e \):

\( E_\gamma \approx \frac{E_e}{3} \).

2. for hadrons: pion production in nuclear interactions \( (p + H \rightarrow p + H + \pi_0; \pi_0 \rightarrow \gamma \gamma) \)

\( \pi_0 \) decay produces the \( \gamma \)'s in this mechanism. For the energy loss one gets for proton energies \( > 1 \) TeV:

\[
\frac{\delta E}{\text{Lightyear}} \approx 20 \text{keV} \cdot \left( \frac{\rho}{1/\text{cm}^3} \right)
\]
For the typical energy one gets \( E_\gamma \approx \frac{E_p}{5} \).

Taking into account the lower mean energy and the fact that only a part of the produced pions decays into \( \gamma \)'s, it can be seen that the nucleonic mechanism is slightly less efficient. However, if the total density of nonthermal hadrons dominates by a large factor (as is suggested by their ratio of about 100 in the Galactic cosmic rays near earth), this \( \gamma \)-ray production mechanism can dominate.

For electrons two other mechanisms operating on ambient radiation fields are often more important than Bremsstrahlung: 3. Synchrotron radiation on an ambient cosmic magnetic field \( B : e + B\text{-field} \rightarrow e + B\text{-field} + \gamma \)

The energy loss is given as:

\[
\frac{\delta E}{\text{Lightyear}} \approx 700\,\text{keV} \cdot \left(\frac{E_e}{\text{TeV}}\right)^2 \cdot \left(\frac{B}{3\,\mu\text{G}}\right)^2 \tag{3}
\]

In the VHE energy range this is more efficient than the mechanism on matter for densities smaller than about 30 cm\(^3\) (i.e. outside dense clouds). The typical energy is quite small however:

\[
E_\gamma \approx 0.05 \left(\frac{E_e}{\text{TeV}}\right)^2 \cdot \left(\frac{B}{3\,\mu\text{G}}\right)^2 \text{eV} \tag{4}
\]

We will see below that photons produced by this mechanism (typically in the radio to X-ray range) have probably been observed together with photons produced by the following mechanism:

4. Inverse Compton scattering on ambient low energy photons with an energy \( E_a \) and an energy density \( U \) (e.g. the thermal photons from the cosmological 3 K background radiation with a typical energy of \( 2 \cdot 10^{-4}\text{eV} \)):

\( e + \gamma \rightarrow e + \gamma \)

with

\[
\frac{\delta E}{\text{Lightyear}} \approx 700\,\text{keV} \cdot \left(\frac{E_e}{\text{TeV}}\right)^2 \cdot \left(\frac{U}{0.22\,\text{eV/cm}^3}\right)^2 \tag{5}
\]

0.22 eV/cm\(^3\) is the energy density equivalent to a magnetic field of 3 \( \mu\)G and close to the density of the 3 K radiation (0.26 eV/cm\(^3\)). For this mechanism the typical energy rises fast with energy:

\[
E_\gamma \approx 1.3 \left(\frac{E_e}{\text{TeV}}\right)^2 \cdot \left(\frac{E_a}{2 \cdot 10^{-4}}\right)^2 \text{GeV} \tag{6}
\]

Consequently at high \( \gamma \)-ray energies this mechanism is often the most important one.

Processes 3. and 4. operate also with protons, but only at energies larger by a factor \((m_p/m_e)^2 \approx 3 \cdot 10^6\), where for typical nonthermal spectra integral flux has typically fallen at least by a similar factor.
Figure 3: The energy spectrum of the supernova remnant 1006 from radio to the TeV \(\gamma\)-range. The flux units are chosen such that equal size on the y-axis corresponds to equal total energy output. This figure was prepared by Mastichiades and de Jager \(^\text{[4]}\) before the CANGAROO collaboration discovered TeV \(\gamma\)-rays above 3 and 1.7 TeV from the NW rim of the remnant. This experimental flux is symbolized by the small horizontal bar which was inserted in the diagram under the assumption of a spectral energy index of \(-2\) (used by CANGAROO in their data analysis). The full lines labeled \(f=1\) etc. are predictions based on fit to the experimental data at low energies (dashed lines) for the total remnant, the predictions only for the NW rim would be about a factor 2-3 lower. For comparison the full line labeled “Crab” shows the TeV energy spectrum of Crab nebula, a “standard candle” which has been measured by various ground-based groups over a large energy range.

2 Supernova remnants, pulsars and the origin of Cosmic Rays

Cosmic rays with energies below the “knee” (see fig.\([\text{I}]\)) are widely believed to be mainly accelerated in “supernova remnants” (“SNR’s”), the debris, consisting of hot thermal matter and a shock wave running into the interstellar medium, of supernova (“SN”) explosions in our Galaxy. The following “standard scenario” for the origin of Galactic cosmic rays is plausible and backed by extensive theoretical work on acceleration of particles in the shock waves induced by the supernova explosion \([\text{I}]\). It is known that about every 30 years a supernova explodes in our Galaxy. From the experimental determination of spallation products in the cosmic rays it is deduced that the mean lifetime of cosmic rays, confined by magnetic fields to the Galaxy, is about \(3 \cdot 10^7\) years. From this one can determine that in order to sustain the above mentioned observed energy density of cosmic rays, about 10 % of the kinetic energy released in a typical SN \((10^{51}\ \text{ergs})\) has to be converted into nonthermal particles. If this scenario is to explain the hadron to electron ratio observed near earth in a simple manner, the hadron to electron ratio in the accelerated particles
SN explosions seem to be the only Galactic phenomena which release enough kinetic energy to sustain the observed cosmic-ray density against losses. In particular pulsars, rapidly rotating magnetized neutron stars, fall short of the required kinetic energy by about an order of magnitude. Direct evidence for the acceleration of cosmic rays in SNR’s is necessary to confirm this scenario.

In 1995 the ASCA satellite observed X-ray radiation from the SNR 1006, the product of a SN explosion in the year A.D. 1006 in a distance of about 1.8 kpc. Based on the measured spectrum and emission region at the rim of the SNR, this radiation was interpreted as being due to synchrotron radiation from electrons recently accelerated in the remnant to energies of up to 100 TeV, which leads to energies for synchrotron radiation in the X-ray range. If this interpretation is correct, a glance at eqs. (3) and (5) makes clear that the SNR should also be a copious emitter of inverse Compton $\gamma$-rays. Their typical energy can be inferred from eq. (4) to lie in the TeV region for electron

---

Figure 4: Sky map of the remnant of the supernova explosion of A.D. 1006 (from Tanimori et al.), a shell with a diameter of about 20 parsecs in a distance of about 1.8 kpc. The grey scale indicates the intensity of $\gamma$ radiation above 3 TeV (for 1996) and 1.7 TeV (for 1997) in units of the signal to shot background noise ratio. The full lines indicate the intensity of X-ray emission (2-10 keV) as measured with the ASCA satellite. The remnant’s shell emits nonthermal x-rays mainly from two rims in the south west and north east- the TeV radiation can be seen to originate only in the latter. The dotted circle is the point spread resolution function of the CANGAROO Čerenkov telescope. The crosses are the directions of maximum x-ray intensity.

---

\(^1\)The question if "$\gamma$-ray bursts" could be important in this respect can not be reliably answered at present.
energies above 10 TeV. Mastichiadis and de Jager\textsuperscript{14} fitted the X-ray and further radio data (which is also believed to have a synchrotron origin) in a model with two free parameters: the magnetic fields strength in the remnant and the spectral index of the power law characterizing the energy spectrum of the remnant (see fig.3). This fit led to quite plausible model parameters (\(\alpha = -2.1\) as expected in first order Fermi acceleration, and a maximal energy of about 20 TeV which is in the theoretically expected range for young SNRs) and predicted the TeV \(\gamma\)-ray flux as a function of one parameter “f”, which is related to acceleration efficiency and the magnetic field strength in the remnant.

The Australian-Japanese CANGAROO collaboration, which operates a Čerenkov telescope with 3.8 m diameter in Woomera, Australia, observed this remnant in 1996 and 1997 and found evidence for \(\gamma\) radiation above 1.7 TeV from the direction of the so called “NW rim” of this remnant\textsuperscript{14} (fig.4). The measured flux is consistent with the one predicted by Mastichiades and de Jager (see fig.3). With this measurement of the inverse Compton component all parameters of their model are fixed. The magnetic field strength in the remnant is about 6 \(\mu\)G and about 1 % of the kinetic energy in this SN explosion was apparently expended to accelerate electrons. The fact that the “SW rim”, which is also bright in X-rays, was not seen by CANGAROO is somewhat surprising and needs further studies. If confirmed by further measurements, this detection of a shell type SNR (with no central neutron star) strongly supports the general idea that the Galactic cosmic-ray electrons are mainly produced in SNR’s.
Because of the theoretical difficulties in predicting the hadron/electron ratio in Fermi acceleration, mentioned in the introduction, independent experimental evidence for the acceleration of hadrons in the required amount in SNR’s is necessary. The predicted VHE $\gamma$-ray fluxes for “average” SNR’s turn out to be at the very limit of the capability of present detectors $^{18}$ and interest concentrated first on remnants which have an “atypically” high density of ambient matter so that the signal due to $\pi_0$ production is large (see section $^{13}$). A prime example is the SNR G78.2+2.1 in a distance of about 1.5 kpc $^{18}$. There is some evidence (from radio and infrared observations) that this remnant is interacting with a dense molecular cloud (“Cong 8”) which would act as a “target” for $\pi_0$ production. It is not completely certain that the cloud is not just superposed on the sky in front of the SNR, moreover it could e.g. be that a strong magnetic field keeps charged cosmic-rays out of it or that the high matter density inhibits the acceleration process $^1$. Leaving these potential complications aside, the expected VHE $\gamma$-ray luminosity of such remnants in the standard “scenario” (i.e. that about 10% of the kinetic explosion energy is expended in acceleration of hadrons) is very high (see fig.5). This SNR was therefore one of the most extensively observed “potential” VHE $\gamma$-ray source, namely by the Whipple telescope in (Arizona, (energy threshold 300 GeV), the HEGRA array of telescopes (Canary Islands, energy threshold 500 GeV) and the HEGRA / AIROBICC (Canary Islands, 12 TeV), Cygnus (New Mexico, 200 TeV) and CASA arrays (Utah, 100 TeV). No evidence for any $\gamma$-ray emission above 300 GeV was obtained by any experiment, some upper limits being more than an order of magnitude below the “naive” prediction. Even if no interaction with the cloud is assumed the flux expected under simple assumptions is about a factor 7 higher than some of the upper limits $^4$, because the ambient interstellar matter density is relatively high at the Galactic location of the SNR (the “Cygnus” region). Somewhat less restrictive results have been obtained from the similar case, SNR “IC 443”. Unfortunately these negative results are not as revealing as a detection of VHE $\gamma$-radiation would have been. As mentioned above, possibilities remain to explain the results for these “atypical” remnants without bringing the “standard scenario” into difficulties. The “standard scenario” remains the most plausible explanation for the origin of the bulk of cosmic rays with energies below the “knee”, but there is as yet no unequivocal experimental evidence for it and thus still room for even qualitatively different explanations (like e.g. an extragalactical origin of the hadronic component $^{20}$). The search for $\gamma$-rays from $\pi_0$ decay from “typical” SNRs like e.g. “Tycho A” is the “experimentum crucis” for the “standard scenario”.

There are three confirmed VHE $\gamma$-ray sources which are powered by pulsars (Crab nebula, Pulsar B1706-44 and Vela pulsar) $^{21}$. As mentioned above, these are probably not directly relevant for the origin of the main part of cosmic rays. These detections allow to learn about processes in the magnetosphere of neutron stars $^{22}$. Moreover the Crab nebula, a steady, bright VHE source, has now assumed the role of a “standard candle” of
Figure 6: Daily integral flux values of VHE γ-ray radiation (energy threshold 1.5 TeV) measured with two independent HEGRA Čerenkov telescopes during 1997. The flux of the Crab nebula (a “reference source”) above this energy is $0.8 \cdot 10^{-11} \text{ cm}^{-2} \text{ sec}^{-1}$. The data points in moon-lit nights (stars) were taken with a reduced operating gain and renormalized to the other measurements.

Two extragalactic VHE γ-ray sources, discovered by the Whipple collaboration, have been extensively studied since 1991: the so called “blazars” Mkn 421 and 501. The most striking observational characteristic of these sources is their extreme flux variability. Mkn 501 was observed in 1995 and 1996 by the Whipple and HEGRA collaborations and had an intensity of about 8% of the Crab in 1995. The intensity rose somewhat in 1996 and entered a variable “high state” in 1997 with maximal fluxes up to 10 times the Crab flux, more than 100 times the discovery flux, making it by far the brightest known VHE source in the sky (see fig.6). In 1998 the source has returned to flux levels of about 40% the Crab flux.

The VHE radiation from Mkn 421 is variable on even smaller time scales down to 15 minutes. The spectrum of Mkn 501 during 1997 has been measured by the CAT, HEGRA, Whipple and Telescope Array collaboration between 0.2 and 30 TeV; as an example the Telescope Array spectrum is shown in fig.6. Like the the spectrum of Mkn 421 it seems to be reasonably approximated by a power law below 5 TeV and has an exponential cutoff at higher energies, similar results have been recently announced by
the Whipple and HEGRA collaboration.

Mkn 421 and 501 are elliptical galaxies both in a distance of about 150 Mpc which probably harbor black holes with masses on the order of $10^6-7$ solar masses in their centers. This black hole accretes ambient matter which emits radiation before it vanishes in the black hole, thus forming an “active galactic nucleus” (AGN). The black hole powers a jet, which streams out with Lorentz factors on the order of 10 at a right angle to the accretion disk. “Blazars” are thought to correspond to AGNs which jet is directed into our line of sight. This ejection of matter is thought to lead to shock fronts and ensuing first order particle acceleration at distances on the order of 10-100 astronomical units from the central black hole. VHE $\gamma$-rays could be produced both by electrons and hadrons. Because of the small ambient matter density, in both cases photons (either ambient or produced via synchrotron radiation of the nonthermal particles) are expected to constitute the “target”.

Fig.8 illustrates models from Pian et al. (27) in which the total electromagnetic spectrum of blazars is explained in a way which bears a qualitative semblance to the model of Mastichiadis, de Jager for SN 1006 (fig.3): in both cases the observed X-rays / TeV $\gamma$-rays are explained as being due to synchrotron / inverse Compton radiation from the same population of freshly accelerated nonthermal electrons. It was observed in 1997 that the intensity variations displayed in VHE $\gamma$ radiation, X-rays and optical radiation of Mkn 501 were simultaneous within the measurement errors (28). This supports the idea of one nonthermal population which explains the whole electromagnetic spectrum. Models based on an hadronic origin of the TeV $\gamma$-rays can also explain all the observed properties, however (29). Because electrons loose energy more readily than hadrons (for the same reasons than their higher efficiency in $\gamma$-ray production), it is a relatively firm prediction that they cannot be accelerated to energies much above 10 TeV in the these blazars (30). Hadrons, on the other hand, have to be accelerated to much higher energies to be viable candidates

\footnote{analogous to the case of the SN ejected matter in the previous section}

\footnote{The fact that this acceleration limit is similar in energy to the one in SN 1006 is purely coincidental.}
as we have seen. So the behaviour of the source spectra around 10 TeV will be a crucial experimental fact for the decision of the basic production mechanism[4]. The cutoff which seems to be indicated above 5 TeV (see fig.1) could be due to such an acceleration limit but also, alternatively due to intergalactic absorption (see next section)[31] with a source spectrum extending to much higher energies, a phenomenon completely unrelated to the source properties. In this connection a prime experimental task is to find more blazars at different distances from our Galaxy. Up to now in searches for further blazars, conducted by the Whipple and HEGRA collaborations, only the blazar “1 ES 2344+514” was uncovered by former group above 300 GeV during one outburst[32].

4 Fundamental physics with cosmic accelerators

Experiments concerning interactions of hadronic cosmic rays in the earth atmosphere stood at the cradle of high-energy physics in the 1940’s and 50’s. A similar area of fundamental research is gaining importance, replacing charged cosmic rays with very-high energy γ-rays and the earth atmosphere with radiation fields in intergalactic space. I discuss a recent particle-physics result using this technique and two other proposals for

\footnote{4 Other interesting arguments in favor of either one mechanism have been advanced[30], but are not conclusive in my opinion}
more advanced studies.

The most important cosmological fields of thermal photons “between the galaxies” are
the 3 K background from the big bang and star light with higher Planck temperatures,
mainly from an era of high star formation in the early universe during a time corre-
sponding to redshift z between of about 1 and 3 or from even earlier times.

VHE γ rays in the TeV range are absorbed in the reaction \( \gamma(\text{TeV}) + \gamma(\text{IR}) \rightarrow e^+ e^- \).

The fact that TeV γ-rays are observed from AGN’s in a distance of about 150 Mpc that
were not absorbed by the infrared background allows to set upper limits on the
density of this background between about 1 and 30 µm wavelength (0.03 eV- 1 eV)
that are lower than experimental limits with any other method. In turn, this allowed Biller et al. to set stringent
limits on a hypothetical radiative decay of primordial neutrinos in a mass range from
0.05 - 1 eV (fig.9). The primordial neutrino density is predicted with great confidence
from the standard big bang theory. A too short lifetime would lead to an overproduc-
cion of cosmological infrared photons.

It seems likely that the absorption of TeV photons sets in slightly above 10 TeV for
the a distance corresponding to the known strong TeV sources Mkn 421 and 501.

The pairs produced in the absorption process will Compton upscatter mainly 3 K
background photons to somewhat smaller energies(eq.(6)). An “intergalactic cas-
scade” (the pendant to an airshower) develops and at low enough energies the cascade
photons will no longer be absorbed. If the
pairs are not deflected by intergalactic magnetic fields they reach the observer from the
same direction and practically the same time as the “original” source photons. If inter-
galactic fields do exist, the pairs are deflected. This has led to two complementary
proposals for fundamental studies with VHE photons:

1. Aharonian et al. considered the case of a relatively strong intergalactic magnetic
field \( > 10^{-10} \text{ G} \), as one might expect not too far away from galaxies. In this case the

\[
\begin{align*}
&\text{Figure 9: Limits on the ratio of radiative lifetime to branching ratio of any massive neutrino species decaying into a much lighter neutrino state and a photon (from Biller et al.\cite{34}). The full (nominal result) and dotted (result allowing for systematic errors in experimental energy scale) lines are the lower lifetime limits derived from VHE observations. The dots are previous lower limits derived with other methods to constrain the infrared background. The standard-model radiative lifetime of a massive Dirac neutrino radiatively decaying via flavor mixing is } \left(10^{36.5} \cdot m_{\nu}^{-5} \cdot \sin^{-2}(\theta) \right) \text{ years (} \theta \text{ is the generational mixing angle), but there are models beyond the standard model that are ruled out with the given neutrino masses by these limits.}
\end{align*}
\]
pairs are strongly deflected and their inverse Compton emission gives rise to a diffuse “pair halo” around sources, emitting $\gamma$ rays well in excess of 10 TeV. It is realistic to detect “pair halos” with the planned arrays of Čerenkov telescopes with a wide field of view. This would allow to determine the “Hubble constant” (a fundamental cosmological parameter) in a novel way, and also to determine the total energy output of VHE sources in a “calorimetric” way, i.e. independent of beaming effects.

2. Plaga\(^{39}\) considered the case of extremely weak intergalactic magnetic fields (smaller then $10^{-15}G$), as they are expected far away from galaxies as a remnant of phase transitions in the very early universe\(^{40}\). In this case the pairs are only slightly deflected, the ensuing $\gamma$-rays reach the observer from the same direction as the source, but are delayed in time due to the a longer travel path. These delayed events have a distinctive distribution in the “delay time versus energy” plane which allows to identify them even in the presence of backgrounds. This is the only method proposed so far which is in principle capable to detect primordial fields as weak as the ones expected from early-universe phase transitions.

One of the most likely extensions of the standard model is supersymmetry\(^{41}\). If supersymmetry is physically realized, the lightest supersymmetric particle (LSP) “$\chi$” is probably stable and within the mass range a plausible candidate for cosmological cold dark matter (CDM). CDM is firmly expected to gravitationally cluster around galaxies including our own Galaxy. The density of LSP’s is largest in the centre of our Galaxy and annihilation of LSP’s is unavoidable. In a recent paper Bergström et al.\(^{42}\) study the question of the expected intensity of $\gamma$-ray’s from annihilation products in the direction of the Galactic centre in a general class of SUSY models, taking into account both detailed calculations of the annihilation cross sections and the expected clustering behaviour of CDM in numerical models. The most distinctive annihilation channels are

\[
\chi \rightarrow \gamma + \gamma \tag{7}
\]

and

\[
\chi \rightarrow \gamma + Z_0 \tag{8}
\]

which occur with branching ratios up to the order of 0.1 %\(^{42}\). The resulting monochromatic $\gamma$-ray lines at $E_\gamma= M_\chi$ resp. $E_\gamma= M_\chi \left(1-M_Z^2/4M_\chi^2\right)$ with intrinsic widths of about $10^{-3}$ “have no plausible astrophysical background whatsoever and would constitute a “smoking gun” of supersymmetric dark matter\(^{42}\)”. This is especially true of the high mass range ($m_\chi > 0.6$ TeV) because the astrophysical $\gamma$-rays produce a background steeply rising with energy (according to $E^{-2.7}$ in the canonical model) and the angular- and energy-resolution capabilities of ground based $\gamma$ detectors improve with rising energy. Fig.\(^{10}\) shows the comparison of 22000 SUSY models considered by Bergström et al. together with the capabilities of existing and next generation detectors. It can be seen that the next generation of ground based VHE $\gamma$ detectors can seriously constrain the SUSY...
parameter range in the high mass region and will be an important supplement to accelerator searches for SUSY. Finally, extreme conditions, that force astrophysicists to use

\[10^{-12} \quad 10^{-11} \quad 10^{-10} \quad 10^{-9} \quad 10^{-8}\]

\[E_{\gamma} \quad \text{[GeV]}\]

\[10^{-13} \quad 10^{-14} \quad 10^{-15} \quad 10^{-16}\]

\[\text{ph cm}^{-2} \text{sec}^{-1}\]

Figure 10: Predicted monochromatic \(\gamma\)-ray flux from a \(10^{-5}\) sr angular region centered on the Galactic center in 22000 generic SUSY models (dots) which yield a density of LSP’s in accordance with the required to explain CDM\(^{[42]}\). The lines are expected upper limits from existing and planned experiments for \(10^6\) seconds observing time of the Galactic centre. “Whipple” is an existing single 70 m\(^2\) Čerenkov telescope, “Granite III’ an upgrade of this instrument, “VERITAS” a planned 9 telescope array on the northern hemisphere “Southern Array” stands for a similar device (like HESS\(^{[12]}\)), situated on the southern hemisphere of earth.

theories far beyond the parameter region known at the time of their original formulation, often prevail in the objects that can be studied with very-high energy \(\gamma\)-rays. The history of physics makes it likely that a more quantitative understanding of such processes, made possible only by using informations from all electromagnetic wavelength bands and neutrinos, will eventually require to invoke “new physics” for their description. A recent concrete proposal in this direction is by Pen et al.\(^{[43]}\) In a certain double Higgs extension of the standard model, “\(\gamma\)-ray bursts”\(^{[15]}\) could be due a high-density induced baryon decay of all baryons in a neutron star.

5 Conclusion

With the detection of VHE \(\gamma\)-rays the physics of the “nonthermal universe” has entered a new era. It is comparable only to the 1950s where the detection of nonthermal radio-emission led to many new insights. But will this lead to a resolution of some of the basic questions in this field, one of which has to be counted as one of the big questions of 20th-century physics (“Where do cosmic
rays come from?""). Probably this will be achieved with data from the next generation of Čerenkov telescopes. In the inquiries about cosmic-ray origin and the mechanism of AGN emission the question of the relative importance of “leptons (i.e. electrons) versus hadrons (i.e. protons and nuclei)” remains open, however. Because there is no “label” on γ-rays, indicating whether they were produced in hadronic or leptonic reactions, the information from the future detection of cosmic VHE neutrinos in detectors like Amanda and others [4] will be crucial.

6 Acknowledgements

I thank my colleagues form the HEGRA collaboration for discussions and supplying material for this review. I thank P.Biermann, M.Baring and H.Völk for clarifications on theoretical issues and S.Denninghoff for a critical reading of the manuscript.

References

1. H. Völk, Particle Acceleration and Gamma-Ray Production in Shell Remnants, in: Proceedings Workshop “Towards a Major Atmospheric Cherenkov Detector V”, (ed.O. deJager, Berg-en-Dal, August 1997) p.87 (Wesprint, Potchefstroom, 1998), http: adswww.harvard.edu, [ proceedings cited below as: TMACD-5]; astro-ph/9711204 and references therein.

2. M.G. Baring, Gamma-ray Production in Supernova Remnants, in: Proc. of XXXIIInd Rencontres de Moriond, “Very High Energy Phenomena in the Universe,” eds. Giraud-Heraud, Y. & Tran Thanh Van, J., (Editions Frontieres, Paris), p. 97; astro-ph/9711177.

3. B. Wiebel, University of Wuppertal report, WUB 94-08.

4. T.C.Weekes et al., VERITAS proposal (1996).

5. T.C.Weekes, Space Science Rev. 75,1 (1996); M.F. Cawley, T.C.Weekes, Exp. Astr. 6,7 (1996).

6. A.Barrau et al. (CAT collaboration), astro-ph/9804046.

7. F.A. Aharonian, A.K. Konopelko, TMACD5 (see ref.1),263, astro-ph/9712044 W. Hofmann, TMACD5 (see ref.1), 284; astro-ph/9710297.

8. G. Yodh et al., TMACD5 (see ref.1),184.

9. T.C. Weekes et al., TMACD5 (see ref.1),202.

10. A. Daum et al., TMACD5 (see ref.1), 178.
11. E. Lorentz, TMACD5 (see ref.1), 415.
12. W. Hofmann, TMACD5 (see ref.1), 405.
13. TMACD5 (see ref.1), 228 (CELESTE); 240 (Mini-GRAAL); 247 (STACEE).
14. A. Mastichiadis, O. C. de Jager, Astron. Astrophys. 311, L5 (1996); astro-ph/9606014
15. G.F. Bignami, these proceedings; J. Greiner, Gamma-Ray Bursts: Old and New, in: Frascati workshop ”Multifrequency behaviour of high energy cosmic sources”, (Vulcan, May 1997), to appear in Mem. Societa Astron. Italiana; astro-ph/9802222
16. K. Koyama et al., Nature 378, 255 (1995).
17. T. Tanimori et al. (CANGAROO collaboration) astro-ph/9801275 (submitted to Ap.J. Letters).
18. T. Naito, J. Takahara, J. Phys. G 20, 477 (1994); L.O’C. Drury et al., A&A 287, 959 (1994).
19. F. Aharonian et al., A&A 285, 645 (1994).
20. R. Plaga, A&A 330, 833 (1998).
21. T. Kifune, TMACD5 (see ref.1), 55.
22. A.K. Harding, O.C. de Jager, TMACD5 (see ref.1), 64.
23. summaries of their VHE properties have been given by: D. Petry, TMACD5 (see ref.1), 2 and S. Bradbury, TMACD5 (see ref.1), 10.
24. M. Kestel (HEGRA coll.), paper submitted to the 25th ECRC, Alcala, (1998).
25. J.A. Gaidos, Nature 383, 319 (1996).
26. N. Hayashida (Telescope Array coll.) et al., subm. to ApJ; astro-ph/9804043.
27. E. Pian et al., ApJ in the press; astro-ph/9710331.
28. M. Catanese et al., Ap.J. 487, L143 (1997).
29. K. Mannheim et al., A&A 315, 77 (1996).
30. J.H. Buckley, Science 279, 676 (1998); K. Mannheim, Science 279, 684 (1998).
31. F.W. Stecker, O.C. de Jager, A&A in the press, astro-ph/9804190.
32. M. Catanese et al., Proc. 25th ICRC (Durban, July 1997) 3, 301 (1997).
33. D. MacMinn, J.R. Primack, Space. Sci. Rev. 75, 413 (1996).
34. S. Biller et al., PRL in the press; astro-ph/9802234.

35. B. Funk et al., Astropart. Phys. in the press; astro-ph/9802308.

36. T. Stanev, A. Franceschini, Ap.J.Lett. 494,L159 (1998).

37. M. Roos, in: Proc. Workshop on Neutrino Physics, (H.V.Klapdor, B.Povh, Heidelberg, 1987), (Springer, Heidelberg, 1988).

38. F.A. Aharonian, F.A. Coppi and H.Völk, Ap.J. 423,L5 (1994).

39. R. Plaga, Nature 430,374 (1995).

40. G. Sigl, A. Olinto and K. Jedamzik, Phys.Rev. D55,4582 (1997).

41. W. De Boer, these proceedings.

42. L. Bergström,P. Ullio and J.H. Buckley, astro-ph/9712318.

43. U. Pen, A. Loeb, N. Turok, PRL in the press; astro-ph/9712178.

44. F. Halzen, Proc. “3rd International Symposium on Sources and Detection of Dark Matter in the Universe (DM98)”, (Santa Monica, Feb. 1998); hep-ex/9804007.