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Very-high-energy gamma astrophysics

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Summary. — High-energy photons are a powerful probe for astrophysics and for fundamental physics under extreme conditions. During the recent years, our knowledge of the most violent phenomena in the Universe has impressively progressed thanks to the advent of new detectors for very-high-energy γ-rays. Ground-based detectors like the Cherenkov telescopes (H.E.S.S. and MAGIC in particular) recently discovered more than 70 new very-high-energy sources. This article reviews the present status of very-high-energy gamma astrophysics, with emphasis on the results related to fundamental physics and on the experimental developments.

PACS `95.55.Vj` – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS `95.85.Pw` – Gamma-ray.
PACS `96.50.S-` – Cosmic rays.

1. – Introduction

The definition of very-high energy (VHE) photons is somehow arbitrary; conventionally we start the VHE region from an energy of 30 GeV (see [1], also for a more comprehensive review on the subject).

The source of high-energy photons from astrophysical objects is mainly gravitational energy released by collapses towards a central massive object. Typically 0.1% to 1% of the energy is emitted in the form of γ-rays. The typical energy (E) spectrum is a power-law $E^{-\Gamma}$; the *spectral index* Γ at the emitter is, according to current models, between 1.5 and 3. The accreting object can be for example a supermassive black hole in the inner part of a galaxy (Active Galactic Nucleus, or AGN), possibly a hypernova in early stage (Gamma-Ray Burst, GRB), a supernova, a binary system.

In addition, one could have characteristic photon signals also from annihilation/decay of heavy particles. In particular, the self-annihilation of a heavy WIMP χ (a candidate dark matter particle) can generate photons. The γ-ray flux from the annihilation of dark

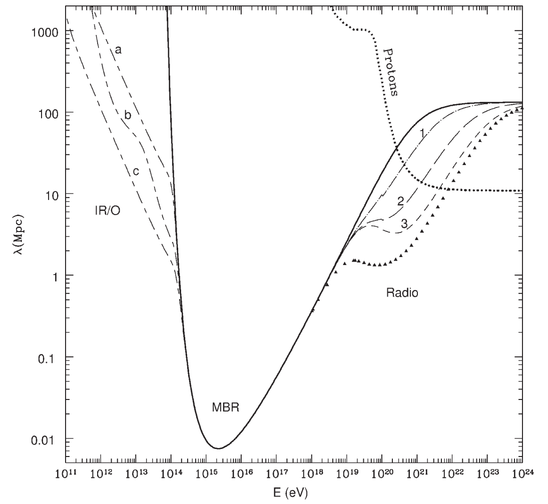


Fig. 1. – Mean free path as a function of the photon energy [2].

matter particles of mass m_{DM} can be expressed as the product of a factor related to the annihilation cross-section times a factor related to density:

$$\frac{\mathrm{d}N}{\mathrm{d}E} = \frac{1}{4\pi}\underbrace{\frac{\langle\sigma v\rangle}{m_{\mathrm{DM}}^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}}_{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega\text{-l.o.s.}} \mathrm{d}l(\Omega)\rho_{\mathrm{DM}}^2}_{\text{astrophysics}} . \tag{1}$$

The particle physics factor contains $\langle\sigma v\rangle$, the velocity-weighted annihilation cross-section (there is indeed a possible component from cosmology in v), and $\mathrm{d}N_\gamma/\mathrm{d}E$, the differential γ-ray spectrum summed over the final states with their corresponding branching ratios. The astrophysical part corresponds to the squared density of the dark matter distribution integrated over the line of sight (l.o.s.) in the observed solid angle.

Finally, some gamma-ray emission could originate in decays of exotic particles of very large mass possibly produced in the early Universe. Such long-lived heavy particles are predicted in many models (*e.g.*, technicolor models or the R-parity–violating SUSY model), and the energy distribution of particles coming from their decay should be radically different from what predicted by the standard emission models from astrophysical sources [3].

2. – Propagation of γ-rays

Electron-positron (e^-e^+) pair production in the interaction of beam photons off extragalactic background photons is a source of opacity of the Universe to γ-rays (fig. 1).

The dominant process for the absorption is the pair-creation process $\gamma + \gamma_{\mathrm{background}} \to e^+ + e^-$, for which the cross-section is described by the Bethe-Heitler formula [4]:

$$\sigma(E,\epsilon) \simeq 1.25 \cdot 10^{-25}(1-\beta^2) \cdot \left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right] \mathrm{cm}^2, \tag{2}$$

where $\beta = \sqrt{1 - \frac{(m_e c^2)^2}{E\,\epsilon}}$, m_e being the value of the electron mass, E is the energy of the (hard) incident photon and ϵ is the energy of the (soft) background photon. Notice that only QED, relativity and cosmology arguments are involved in the previous formula.

The cross-section in eq. (2) is maximized when $\epsilon \simeq \frac{500\,\mathrm{GeV}}{E}$ eV. Hence if $E = 1$ TeV the interaction cross-section is maximal when $\epsilon \simeq 0.5$ eV (corresponding to a near-infrared soft photon). In general, for very-high-energy photons the $\gamma\gamma \rightarrow e^+ + e^-$ interaction becomes important with optical/infrared photons, whereas the interaction with the cosmic microwave background becomes dominant at $E \sim 1$ PeV. Therefore, the background component relevant for interaction with VHE photons is the optical/infrared background radiation. This is called the extragalactic background light (EBL) [5].

The EBL consists of the sum of starlights emitted by galaxies throughout their whole cosmic history, plus possible additional contributions, like, *e.g.*, light from hypothetical first stars that formed before galaxies were assembled. Therefore, in principle the EBL contains important information both the evolution of baryonic components of galaxies and the structure of the Universe in the pre-galactic era.

The attenuation suffered by observed VHE spectra can thus be used to derive constraints on the EBL density [6].

3. – Detection techniques

The detection of high-energy photons is complicated by the absorption by the atmosphere, and by the faintness of the signal, in particular when compared to the corresponding charged particles of similar energy.

3˙1. *Atmospheric transparency and processes of interaction.* – Photons above the ultraviolet (UV) region are shielded by the Earth's atmosphere.

Photons interact with matter mostly due to the Compton mechanism and to the photoelectric effect at energies up to about 20 MeV, while e^+e^- pair production dominates above about 20 MeV. Above about 50 GeV the production of atmospheric showers bevomes sizeable, dominated by the pair production and the bremsstrahlung mechanisms: an energetic photon scatters on an atmospheric nucleus and produces a pair, which emits secondary photons via bremsstrahlung; such photons produce in turn an e^+e^- pair, and so on, giving rise to a shower of charged particles and photons. The process is described, *e.g.*, in [7, 8].

At sea level the thickness of the atmosphere corresponds to about 28 radiation lengths. This means that only satellite-based detectors can detect primary X/γ-rays. Since the fluxes of high-energy photons are low and decrease rapidly with increasing energy, VHE and UHE gammas can be detected only from the atmospheric showers they produce, *i.e.* by means of ground-based detectors; such detectors should be placed at high altitudes, where atmospheric dimming is lower.

Ground-based VHE telescopes such as MILAGRO, ARGO, CANGAROO, H.E.S.S., MAGIC and VERITAS detect the secondary particles of the atmospheric showers produced by primary photons and cosmic rays of energy higher than the primaries observed by satellites.

There are two main classes of ground-based HE gamma detectors: the Extensive Air Shower arrays (EAS) and the Cherenkov telescopes.

The EAS detectors, such as MILAGRO and ARGO, are made by a large array of detectors sensitive to charged secondary particles generated by the atmospheric showers. They have high duty cycle and a large Field of View (FoV), but a low sensitivity. Since

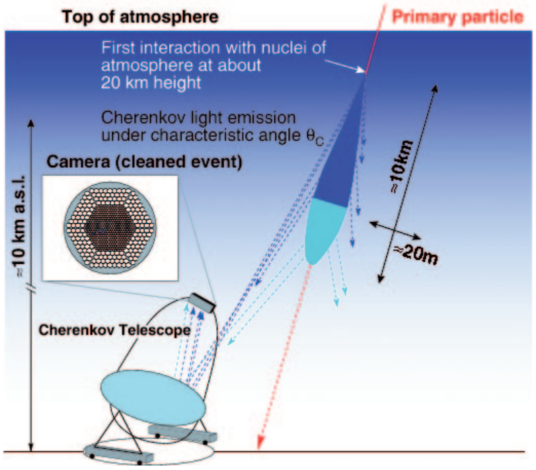


Fig. 2. – The observational technique adopted by the Imaging Atmospheric Cherenkov Telescopes (IACTs) [9].

the maximum of a photon-initiated shower at 1 TeV typically occurs at 8 km a.s.l., the energy threshold of such detectors is rather large.

Imaging Atmospheric Cherenkov Telescopes (IACTs), such as CANGAROO, H.E.S.S., MAGIC and VERITAS, detect the Cherenkov photons produced in air by charged, locally superluminal particles in atmospheric showers. They have a low duty cycle and a small FoV, but they have a high sensitivity and a low energy threshold.

The observational technique used by IACTs is to project the Cherenkov light collected by a large optical reflecting surface onto a camera made by an array of photomultiplies in the focal plane of the reflector (see fig. 2). The camera has a typical diameter of about 1 m, which corresponds to a FoV of $5^{\rm o} \times 5^{\rm o}$.

In the GeV-TeV region the background from charged particles is three orders of magnitude larger than the signal. Hadronic showers, however, have a different topology with respect to electromagnetic showers, being larger and more subject to fluctuations. One can thus select showers induced by gamma-rays.

Systems of more than one Cherenkov telescope provide a better background rejection, and a better angular and energy resolution than a single telescope.

The main characteristics of the main IACTs are summarized in table I.

4. – The emerging VHE gamma-ray sky

Thanks mostly to Cherenkov telescopes, a large amount of VHE sources has been detected and identified (see fig. 3). When this review has been written (April 2009), more than 80 VHE sources had been detected (only 4 were known in 2004), acting as cosmic particle accelerators. About two thirds are galactic, and one third is extragalactic.

Large part of the currently known galactic TeV sources remain unidentified. This is in part due to the difficulty of identifying extended sources with no clear sub-structure. Nonetheless, several methods of identification have been successfully applied and the situation is much more favourable than that in the GeV band where only one galactic

TABLE I. – *Main characteristics of currently operating IACTs. The energy threshold given is the approximate trigger-level threshold for observations close to zenith. The approximate sensitivity is expressed as the minimum flux (as a percentage of that of the Crab Nebula:* $\approx 2 \times 10^{-11}$ *photons* $\text{cm}^{-2}\ \text{s}^{-1}$ *above* 1 TeV*) of a point-like source detectable at the* 5σ *significance level in a* 50 *hour observation.*

Instrument	Lat. (°)	Long. (°)	Alt. (m)	Tels.	Tel. Area (m^2)	Total A. (m^2)	FoV (°)	Thresh. (TeV)	Sensitivity (% Crab)	Sp. res. (°)
H.E.S.S.	-23	16	1800	4	107	428	5	0.1	0.7	0.05
VERITAS	32	-111	1275	4	106	424	3.5	0.1	0.7	0.06
MAGIC	29	18	2225	2	236	472	3.5	0.05	0.8	0.07
CANGAROO-III	-31	137	160	3	57.3	172	4	0.4	15	0.1

source class (pulsars) has been unambiguously identified. The new results by the Fermi telescope will tell.

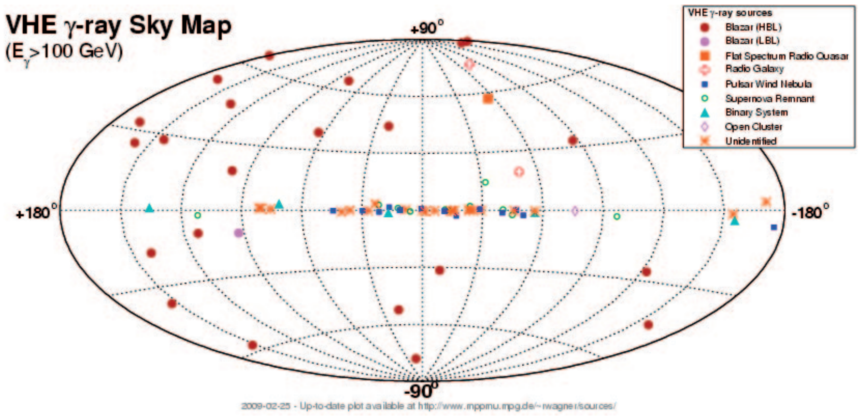
Whatever the details, the detection of photons with $E \gtrsim 100\,\text{TeV}$ from supernova remnants is a proof of the acceleration of primary particles in supernova shocks to energies well above 10^{14} eV. This is getting close to the knee of the cosmic-ray spectrum; this fact might signal the high-energy end of the galactic cosmic-ray distribution. Circumstantial evidence supports a hadronic origin for at least part of the VHE emission.

Very recently, the MAGIC Collaboration has reported on the detection of the Crab pulsar at VHE [11].

Some of the observations are particularly relevant for fundamental physics.

4·1. *The search for products of DM annihilations.* – An observation of the Galactic Centre and of several satellites of the Milky Way gave at present no result.

4·2. *Study of the propagation from large distances.* – About 30 AGN have been detected as VHE sources by the time this review is written (April 2009). The AGN observed at VHE are uniformly distributed in the high galactic latitude sky. Measured spectral indices are plotted *versus* redshift in fig. 4.



2009-02-25 - Up-to-date plot available at http://www.mppmu.mpg.de/~rwagner/sources/

Fig. 3. – Known sources in the VHE sky in April 2009 [10].

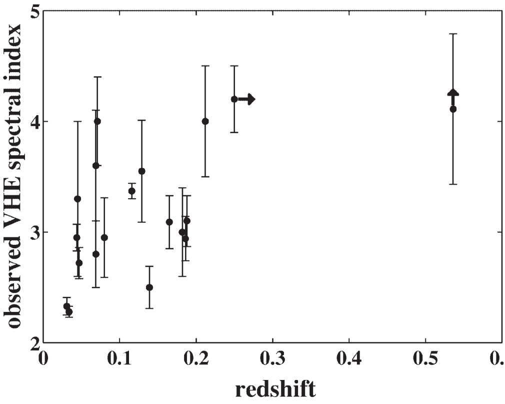


Fig. 4. – Observed spectral indexes for AGN in the VHE region.

Currently, the most distant established VHE source is 3C 279 [12], with $z = 0.536$.

The TeV spectra of blazars can be used as probes of the EBL. The TeV photons emitted by a blazar interact with the EBL photons and are likely absorbed via pair production. Whatever its intrinsic shape at emission, after traveling through the EBL-filled space, a blazar spectrum will reach the observer distorted by absorption. The strength of the absorption is measured by the optical depth $\tau(E, z)$ for the attenuation between the blazar, located at a distance redshift z, and the Earth [13]. Based on the inferred attenuation of blazar VHE emission by the EBL, and in particular on the detection of the distant ($z = 0.536$) quasar 3C 279, the transparency of the Universe at VHE γ-rays is deduced to be maximal, at the level implied by the known cosmic evolution of the stellar populations of galaxies.

Other interactions than the one just described might change our picture of the attenuation of γ-rays, and they are presently subject of thorough studies, since the present data on the absorption of photons are hardly compatible with the pure QED picture. For example, γ-rays might interact with (possibly quintessential) very light axion-like particles, which might change the absorption length [14, 15]. In particular, in the DARMA model [15], such contribution might enhance the photon flux via a regeneration mechanism. Such an interaction would be mediated by the (intergalactic) magnetic fields. A similar mechanism invokes the conversion of photons into axion-like particles at the emission source [16].

Finally, mechanisms in which the absorption is changed through violation of the Lorentz invariance as in ref. [17] are also under test; such models are particularly appealing within scenarios inspired to quantum gravity [18].

4˙3. *Studies related to flares.* – The known TeV blazars are variable in flux in all wavebands. Blazar variability, both in flux and spectrum, has been observed at VHE frequencies down to minute timescales. For Mkn 501, a rapid flare occurred on the night of July 10th, 2005, showing a doubling time as short as about 2 minutes and a delay of about 3 minutes as a function of energy of the emitted photons.

The H.E.S.S. observations of PKS 2155-304 (located at $z = 0.116$), showed a very fast flux variability: on the night of July 28th, 2006 it had a peak flux about 50 times its average flux (and about 15 times the Crab flux), and rapidly doubled it in four successive episodes (in $67 \pm 50\,\mathrm{s}$, $116 \pm 50\,\mathrm{s}$, $173 \pm 50\,\mathrm{s}$, and $178 \pm 50\,\mathrm{s}$, respectively). It is amazing the fact that the Schwarzschild radii of the black holes powering such AGNs are two orders of magnitude larger.

The variability of the AGN in the VHE region provides information about possible violations of the Lorentz invariance (LIV). The velocity of light can be parametrized as [18]

$$V = c\left[1 + \xi\left(\frac{E}{E_{s1}}\right) + \dots\right], \tag{3}$$

where the ξ's are parameters of order unity which can be positive or negative. At first order photons of different energies emitted at the same time are detected with a time delay $\Delta t \simeq \xi \frac{E}{E_{s1}} \frac{z}{H_0} = \xi \frac{E}{E_{QG}} \frac{L}{c}$. The MAGIC data about Mkn 501 [19] showed at 2σ a correlation between the arrival time of photons and their energy. Higher energy photons arrive later, at a rate of $(0.030 \pm 0.012)\,\mathrm{s/GeV}$. If interpreted as LIV at linear order, this yields, according to eq. (3), to $(s1/\xi) \sim M_P/30$, where $M_P \simeq 1.2 \times 10^{19}\,\mathrm{GeV}$ is the Planck mass.

H.E.S.S. observations of PKS 2155 [20] evidenced no effect, allowing to set a lower limit $(s1/\xi) > 0.04\ M_P$.

In the observation of the GRB080916C [21] at a photometric redshift of 4.35 ± 0.15 the Fermi experiment has observed a correlation between the energy and the time of arrival of photons; in particular the most energetic photon, at $E = 13.2^{+0.70}_{-1.52}\,\mathrm{GeV}$, has arrived at 16.54 seconds after the primary burst. If we consider the time delay of $(0.030 \pm 0.012)\,\mathrm{s/GeV}$ at $z = 0.034$ and we extrapolate it through

$$\Delta t = \frac{1}{H_0} \frac{E}{E_{s1}} \int_0^z \mathrm{d}\zeta \frac{(1+\zeta)}{\sqrt{\Omega_m (1+\zeta)^3 + \Omega_\Lambda}}, \tag{4}$$

we obtain, using a standard $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, $h = 0.71$ cosmology, $\Delta t = (50 \pm 20)\,\mathrm{s}$.

5. – The future

A second MAGIC telescope, at a distance of 85 m from the first one, started operating in April 2009. With this new telescope, MAGIC enters in phase 2 (MAGIC 2). The H.E.S.S. Collaboration has started the construction of a large telescope, which will be inaugurated in 2010. This will lead the instrument into its phase 2 (H.E.S.S. 2). With its diameter of 28 m, the new telescope, located in the middle of the four existing telescopes, and it should decrease the trigger threshold to some 20 GeV.

Longer-term projects for ground telescopes are under discussion; one in particular, the Cherenkov Telescope Array (CTA), has a huge European involvement. The CTA facility is meant to explore the sky in the energy range from 10 GeV to 100 TeV and it is designed to combine guaranteed science with significant discovery potential.

The CTA is a cornerstone towards a multi-messenger exploration of the Universe. In the most ambitious and expensive scheme, for which the cost foreseen is of the order of 100–150 million euros, it should allow mapping the Universe in that energy range with a sensitivity of 0.001 Crab.

6. – Conclusions

High-energy photons are a powerful probe of fundamental physics under extreme conditions, since they are produced in the highest energy phenomena, they often travel through large distances, and their interactions display large boosts towards the center of mass.

Observation of X- and γ-rays gives an exciting view of the HE universe thanks to satellite-based telescopes (AGILE, GLAST) and to ground-based detectors like the Cherenkov telescopes, which discovered more than 70 new VHE sources in the last five years and are going on this way. This large population of VHE-γ-ray sources, which are often unknown sources, poses questions on the transparency of the Universe at these energy ranges; this might indicate the existence of new physics.

The progress achieved with the latest generation of Cherenkov telescopes is comparable with the one drawn by EGRET with respect to the previous γ-ray satellite detectors.

This exciting scenario gives handles for the study of new mechanisms about the VHE-γ-ray origin and propagation, and many astrophysical constraints are feeding the theories.

The exploration of the VHE sources has just started and in the next three years (2010/2012) a factor of 2 improvement in the TeV range will be can be expected by MAGIC 2, H.E.S.S. 2, and VERITAS.

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