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TeV gamma rays from AGNs

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Abstract: A review of the observations of Active Galactic Nuclei at Very High Energies (GeV/TeV) is provided. The contribution of these observation to the understanding of the physics of these astrophysical objects and of the optical to infrared background radiation field is examined.

Dedicated to E. B.

1. The Very High Energy window

Astronomy at energies above 100 GeV (Very High Energy or VHE range) is only possible by means of the detection of the air shower generated by the γ-ray as it enters the Earth's atmosphere. The most successful detectors in this energy range are the so-called Imaging Air Cherenkov Telescopes (IACTs) which use the Cherenkov radiation produced by the charged particles in the shower to reconstruct the primary γ-ray direction and energy [1, 2]. IACTs benefit from the huge detection areas (in the order of 5×10^4 m^2) as compared to detectors on board satellites although suffer from reduced duty cycles around 15%. Currently operating IACTs have an energy resolution ranging from 10% to 40%, an angular resolution for individual events of about 0.1°-0.2°, a field of view of a few degrees times a few degrees and sensitivities below 10^{-11} cm^{-2} s^{-1}. The characteristics of the most important Cherenkov installations around the world are tabulated in table 1.

A number of sources have been firmly established in the VHE range. The VHE catalog [3] comprises galactic sources like pulsars/plerions (Crab Nebula -the standard candle at these energies-, PSR 1706 and Vela) and shell-type Supernova Remnants (SN 1006, Cas A and RXJ 1713), and extragalactic Active Galactic Nuclei (AGN, Mrk 421, Mrk 501, 1ES 2344, 1ES 1959 and BL Lac). The latter will be the subject of this review.

AGN are non-nuclear sources, i.e., they are fed by gravitational accretion and not by nuclear reactions. The standard picture of an AGN involves a supermassive (10^8-10^9 solar masses) black hole accreting matter from an accretion disc. In a radio-loud AGN a strong

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Telescope	Whipple	CAT	HEGRA system	HEGRA CT1	CANGAROO	TA
Site	Arizona	Themis	La Palma	La Palma	Woomera	Utah
Elevation (m)	2300	1650	2220	2220	160	1600
Number tel.	1	1	5	1	1	3
Mirror (m^2)	74	18	5×8.4	10	11.3	5×6
Thresh. (GeV)	250	300	500	650	1000	600

Table 1: Characteristics of some of the currently operating Cherenkov telescopes. HEGRA is made up of two detectors: a classical standalone telescope and an innovative stereoscopic system of 5 telescopes.

jet of relativistic particles surges perpendicular to the accretion disc and extends to Mpc distances. The generation of the jets is still not well understood. All five VHE AGN belong to the "blazar" type (in particular to the BL Lac sub-type), which is characterized by non-thermal emission, rapid variability and VLBI superluminal motion. They are radio-loud and their radio emission arises from the source core. In blazars we look towards the core along the jet axis and the observed radiation is strongly amplified by relativistic beaming.

The spectral energy distributions (SED), which measures the energy output at the different frequencies, of blazars normally displays two broad peaks, a low energy component centered between IR and X-rays depending on the AGN and which plausibly arises from synchroton emission of high energy electrons in the jet, and a high energy component between X-rays and VHE, which is generally believe to be due to inverse Compton scattering of low energy photons. These photons may be the same synchroton photons involved in the low energy peak (self-synchroton-compton model, SSC [4, 5]) or belong to some external field (external compton model, EC [6]). Alternatively VHE gammas could be secondary products of a proton-initiated shower (PIC model [7]).

The number of extragalactic sources detected at VHE does not agree with a simple extrapolation of the detections at lower energies, namely the almost 100 AGN detected by EGRET at energies around 1 GeV. The most plausible explanation is that AGN are absorbed in the intergalactic infrared (IR) background[8]. VHE γ-rays of energy E_γ collide with low energy background photons γ_{bg} of energy ϵ_{bg}: $\gamma_{VHE} + \gamma_{bg} \to e^- + e^+$. This process peaks at 1.5×10^{-25} cm^2 for $\lambda_{bg}(\mu\ m) \simeq 1.24\ E_\gamma$ (TeV). The result is an exponential cutoff in the energy spectrum of VHE sources which depend on the distance to the source.

The non-detection of sources at VHE allows in turn to set limits on the extragalactic IR background. One can use those sources which have been detected to set even more stringent limits by trying to find the exact position of the exponential cutoff in the energy spectrum.

2. General description of the VHE sources

The best observed VHE BL Lacs are Mrk 421 and Mrk 501. They both belong to the so-called blue or X-ray selected BL Lacs whose low energy peak is situated at X-ray energies. They are the closest AGN detected by EGRET at energies around 1 GeV and are situated at very similar distances: redshift z=0.031 (a distance of ∼150 Mpc). Both blazars are time variable and show strong flaring activity.

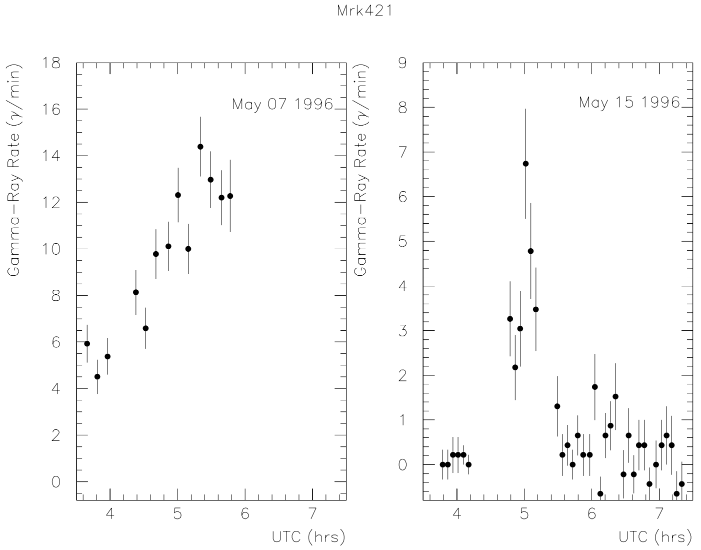

Figure 1: Temporal evolution of Mrk 421 during its 7 May and 15 May 1996 flares as observed by the Whipple telescope. The integration time is respectively 9 and 4.5 min. From [11].

Mrk 421 was the first extragalactic object to be discovered as a VHE emitter [9, 10]. The synchroton peak of the SED moves from around 50 eV at quiescent state to ∼0.5 keV for strong flares (see below). It shows extremely fast flux changes with doubling times as short as 15 minutes as reported by Whipple[11] in May 1996 and shown in figure 1. Such a short flare was used to establish a jet Doppler factor of δ ∼10 and an emission region smaller that 10 light hours. These numbers set strong constraints on the mechanism responsible for the VHE production. Mrk 421 has exhibited several flaring periods, the longest one in the first months of 2001.

Mrk 501 was the second BL Lac to be discovered as a VHE source [12, 13]. During the first two years after its discovery it remained in a quiescent state well below the Crab flux. However in March 1997 the source went into a state of highly variable emission at a level as high as 10 crabs. High activity was also reported by the instruments on board the X-ray satellite RXTE. The synchroton peak of the SED is at even higher energies than Mrk 421 and shows a wider variability range from ∼50 eV to ∼50 keV in the strongest flares.

3. Time variability

All VHE telescopes have monitored Mrk 421 and Mrk 501 extensively during the past years. Mrk 421 has now been covered in VHE for more than 5 years. It has gone through a number of flares that have culminated in a long period of enhanced activity in the first months of 2001. The correlation between the variability at VHE and at lower wavelengths is supported by several multiwavelength campaigns. Observations conducted with Whipple, EGRET (∼1 GeV γ-rays), ASCA (soft X) and several UV, IR and radio detectors back in

1994[19, 20], even if clearly undersampled, revealed already that there was some correlation between VHE and soft X during a very short flare. All other wavelengths showed no evidence of variability.

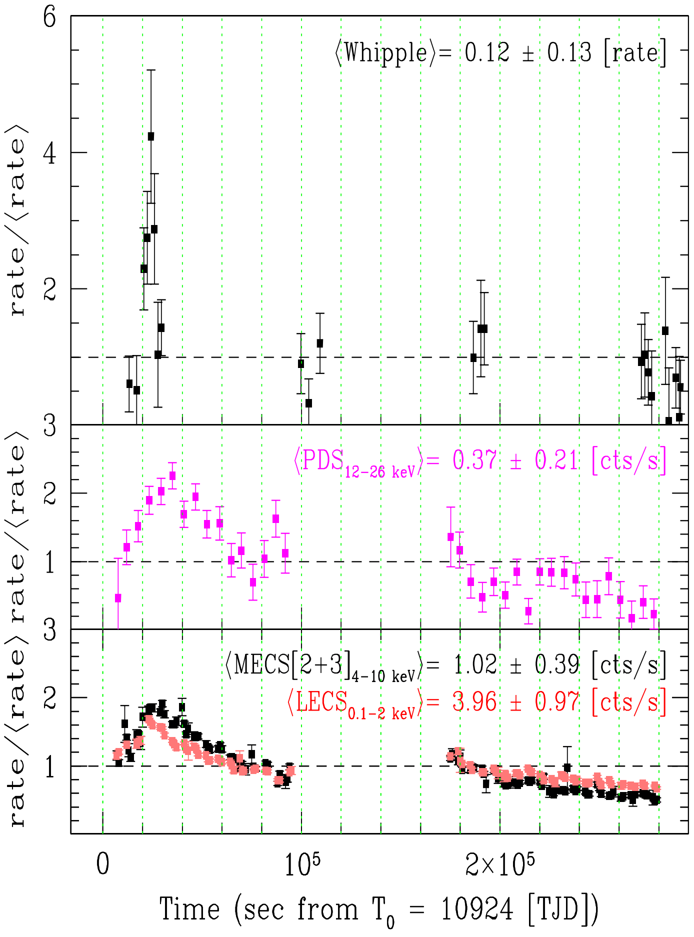

Figure 2: Light curves for observations of Mrk 421 in April 1998 by Whipple and Beppo SAX. Figure from [22]

A multiwavelength campaign in 1995[21] showed for the first time clear correlations between VHE and X. Again no detection was possible in ∼1 GeV γ-rays, but correlated variations were observed in UV and optical. The observations were still greatly undersampled. However two campaigns in 1998 coordinating long exposures of Whipple, CAT and HEGRA, along with the X-ray satellites ASCA and Beppo-SAX[22, 23] finally established the first hour-scale correlations between X and VHE. As an illustration figure 2 shows a very fast flare simultaneously observed both in Whipple and Beppo SAX. The peak occurs at the same time within 1 hour, but the falloff is considerably slower in X-rays. HEGRA reported again very fast variability during a campaign with RXTE and correlation between both energy bands[24].

The long Mrk 421 flaring episode in 2001 and some short events in 2000 have produced a wealth of multiwavelength information much of which is to be published soon. Again simultaneous observations with HEGRA, Whipple, CAT along with RXTE and Beppo SAX evidence X/VHE correlation on all time scales[25, 26, 28, 27, 29]. The flux variations measured with HEGRA CT1 and ASM and independently Whipple and ASM have been found to be both correlated with a correlation factor r=0.67[25, 26] and no time lag (0±0.5 days).

The first multiwavelength observations of Mrk 501 were performed in 1996 by Whipple, EGRET, ASCA and an optical telescope[31], but they were too undersampled. The situation changed radically in 1997, when all VHE observatories reported correlated VHE, X-ray, soft γ-ray and UV variability.

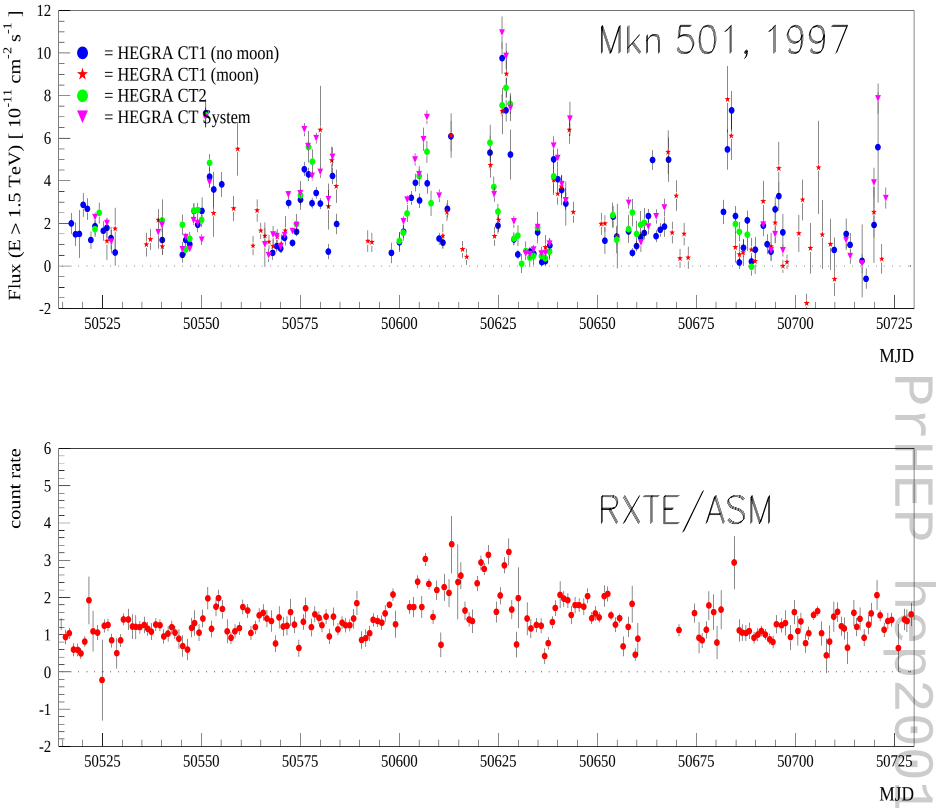

Figure 3: Top: VHE flux above 1.5 TeV as measured by HEGRA. Bottom: X-ray count rate in the 2-10 keV energy range as measured by ASM.

Figure 3 shows the VHE light curve of Mrk 501 during its 1997 flare, as measured by both instruments in HEGRA, together with the X-ray light curved obtained with ASM on board RXTE [32]. Both samples were found to be correlated with correlation factor r=0.61 (8σ significance) and no time lag (see also [33]). A search for quasi-periodic oscillations[34] using a shot noise model provides evidence for a 23 day period in both curves. (This analysis was only possible because data taken with HEGRA CT1 during moon time were available.) The interpretation of this period is controversial: it could be due to precession of the accretion disc, the effect of a close binary system of supermassive black holes in the center of the AGN or due to radiating clumps on helical trajectories.

The extremely short flare of Mrk 421 reported by Whipple in 1996 has also allowed to test Quantum Gravity (QG). Some of these models predict measurable time delays if the particles have energies close to the QG scale or if they have traveled cosmological distances. A lower limit of 4×10^{16} GeV could be placed on the relevant QG energy scale by looking at time differences between 1 TeV and 2 TeV photons during the 1996 flare[35].

4. Spectral energy distributions

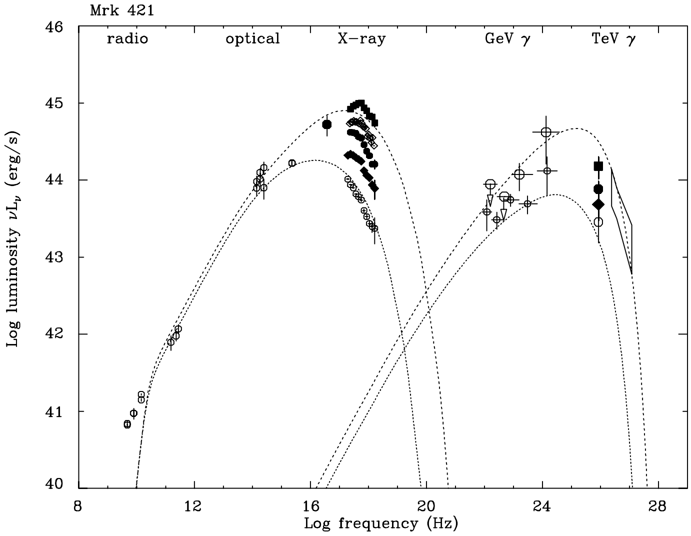

Figure 4: Evolution of Mrk 421 SED. The dotted line represents the best SSC fit for the quiescent/flare state. Figure from [14].

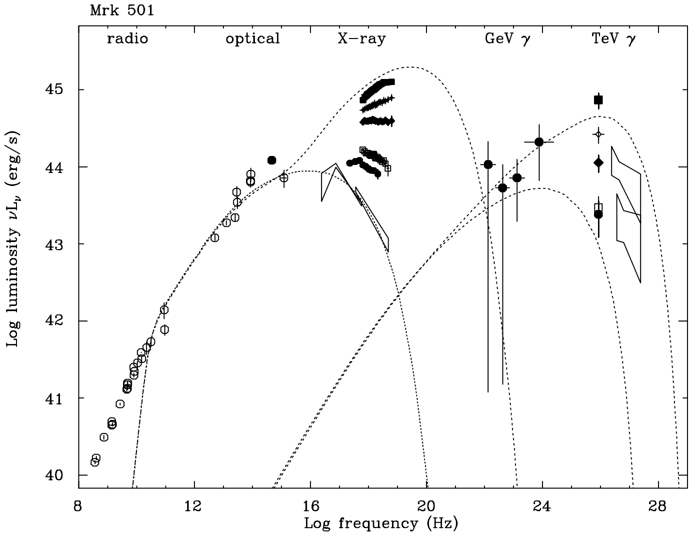

Figure 5: Evolution of Mrk 501 SED. The dotted line represents the best SSC fit for the quiescent/flare state. Figure from [14].

Figures 4 and 5 represent the evolution of the SED for both AGN during 5 years of multiwavelength campaigns [14] and illustrate some of the above mentioned features. A clear correlation can be seen between the keV X-ray and the VHE flux, whilst only small changes are observed in the MeV/GeV range. As mentioned above, the shift in both peaks is much larger for Mrk 501. As a consequence only small variations in the X-ray and VHE spectral indices are observed in Mrk 421 (which is always $\Gamma_X \sim \Gamma_{VHE}$ 3). In contrast the slope of the X-ray spectrum for MKn 501 ranges from $\Gamma_X \sim 1.7$ to $\Gamma_X \sim 2.5$ while the VHE slope remains almost unchanged around $\Gamma_{VHE} \sim 2.5$.

Simultaneous SED can be used to constrain the magnetic field strength (B) and the Doppler factor (δ) of the jet. A number of authors have used the SSC model to conclude that δ ranges between 15 and 40 and B=0.03-0.9 G for Mrk 421[15, 16], and $\delta \sim$ 1.5-20 and B=0.08-0.2 G for Mrk 501 [17, 16]. Proton models would call for B=30-90 G for $\delta \sim$10[18]. In addition it can be said that the correlation of X-ray and VHE is consistent with IC models where the same population of electrons radiate the X-rays and the VHE γ's.

5. VHE spectra

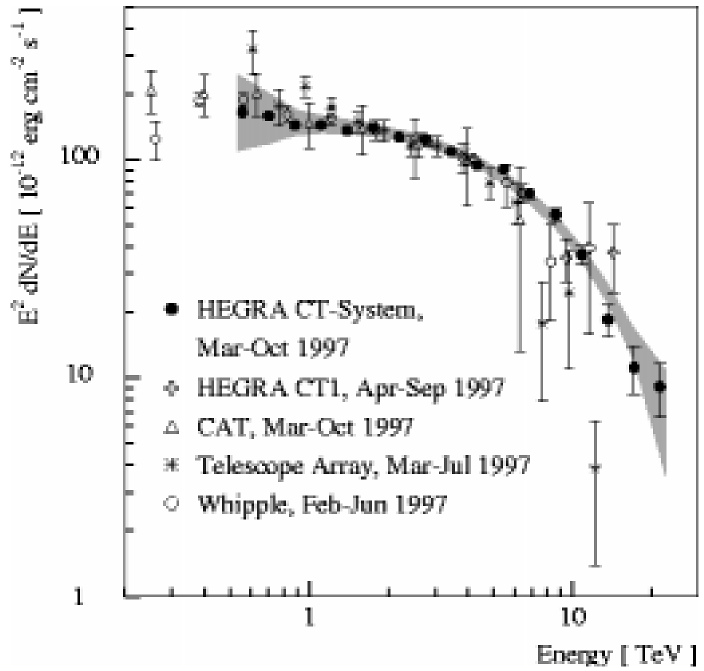

Figure 6: The energy spectrum of Mrk 501 as measured by several IACTs during its 1997 flare.

The high flux VHE emission during their flaring episodes and improved telescope sensitivities have allowed detailed spectra of Mrk 421 and Mrk 501 to be extracted. Figure 6 shows the VHE energy spectrum during the 1997 flare of Mrk 501 as determined by HEGRA, CAT, the Telescope Array and CAT (see [36] and references within). They all show remarkable agreement. The improved energy resolution and high statistics at energies above 10 TeV permit the HEGRA CT system to establish that the spectrum is curved. A fit to a single power law can be rejected. Only adding an energy cutoff provides satisfactory results with differential spectral index α=1.9±0.2 and energy cutoff E_0=6.2±3.5 TeV. The general opinion was that this cutoff is due to VHE γ absorption in the intergalactic IR background (see last section), although an intrinsic cutoff could not be ruled out.

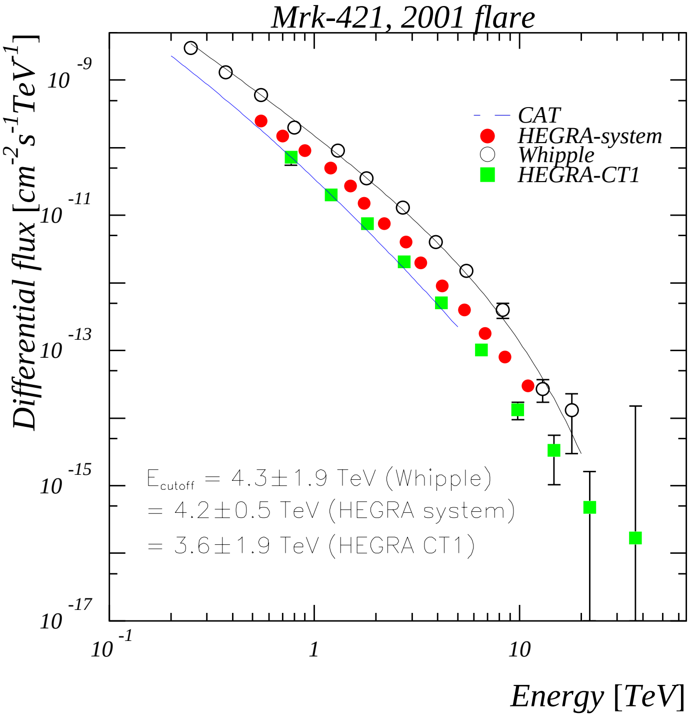

Figure 7: The energy spectrum of Mrk 421 as measured by several IACTs during its 2001 flare.

Further evidence in favor of an IR-induced cutoff have been provided by the analysis of the recent data on Mrk 421 during its 2001 flare. Mrk 421 and Mrk 501 are at almost the same distance, so they are expected to show very similar IR cutoffs, whilst one would expect different intrinsic cutoffs from the fact that their SEDs are substantially different. All the groups agree to a curved spectrum with an energy cutoff around 4±2 TeV[25, 30, 27, 28], consistent with the cutoff energy observed for Mrk 501.

The observed cutoff in the spectrum of Mrk 501 has allowed to set very restrictive limits on the amount of IR extragalactic light, in a spectral range where a direct measurement is technically difficult. An accurate measurement of the optical to IR extragalactic background is instrumental to constraint the models of star and metal formation.

An analysis performed on the basis of the HEGRA data resulted in an upper limit of 1.1×10^{-3} eV/cm^3 at $\sim$25 μm[38]. This limit improves the existing limits based on direct observations in almost an order of magnitude. Actually its partial inconsistency with some measurements[39] has induced some authors to suggest that VHE γ's may be in fact faked by the coherent arrival of lower energy photons or that Lorentz invariance may be broken at TeV energies[40]. However the most probable explanation is that the IR direct background measurements are contaminated by foreground IR sources.

Even though the Mrk 421 2001 flare has brought about firm evidence in favour of extragalactic absorption as responsible for the VHE energy cutoff, it would be desirable to base any final conclusion on more than two sources. Other BL Lacs (1ES 2344, 1ES

1959, BL Lac and 3C 66A) have been reported at VHE by only one instrument, but have never been confirmed by the others, probably because they are in the limit of the telescope sensitivity and the emission was episodic. Recently HEGRA has confirmed the detection of 1ES 2344 and reported an energy spectrum that may be compatible with the expected IR absorption[37].

6. Conclusions

VHE astronomy is now consolidated in the 300 GeV - 20 TeV energy range with a number of galactic and extragalactic sources. Only BL Lacs have been firmly established as extragalactic sources. The observational features support the current AGN models based on synchroton plus IC emission of a primary population of high energy electrons. The energy spectra above 1 TeV strongly hints to VHE absorption in the infrared background.

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