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THE ARGO−YBJ SENSITIVITY TO GAMMA-RAY EMISSION FROM BLAZARS

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ABSTRACT

The ARGO−YBJ (Astrophysical Radiation with Ground-based Observatory at YangBaJing) experiment is a "full coverage" air shower detector currently under construction at the Yangbajing Cosmic Ray Laboratory (Tibet, China, 4300 m a.s.l.). The full coverage approach and the high altitude location allow the study of a wide range of fundamental issues in cosmic ray and astroparticle physics, including gamma-ray astronomy at energies higher than a few hundreds GeV. In this paper we present the expected sensitivity to detect point gamma-ray sources, paying particular attention to blazars.

1 Introduction

ARGO−YBJ is an Extensive Air Shower (EAS) detector optimized to observe small-size showers. It consists of a layer of Resistive Plate Counters (RPCs) covering an area of $\sim$6500 m^2 and it is located in the Yangbajing Cosmic Ray Laboratory (Tibet, P. R. China) at an altitude of 4300 m, latitude 30.11^{o}N and longitude 90.53^{o}E. Devoted to a wide range of fundamental issues in cosmic ray and astroparticle physics [1], ARGO$-$YBJ will survey in particular the γ-ray sky in the energy range 300 GeV$-$20 TeV, bypassing the limitation of the Cherenkov technique to pointed observations.

A detailed description of the expected sensitivity to the Crab Nebula signal can be found elsewhere in this proceedings [2]. The significance of this signal in 1 year observation time as a function of the minimum pad multiplicity N_{pad} can be converted into the sensitivity to γ-ray point sources presented in fig.1, by associating each value of N_{pad} to the corresponding median energy E_{med}. The purpose of using the median energy is that it reduces the effects of the choice of the spectral index utilized in the determination of the detector sensitivity. Since the value of the spectral index is often assumed or not well determined, this is important in ensuring that an accurate integral flux value is calculated. The result is that ARGO$-$YBJ, at an energy threshold of $\sim$1 TeV, will observe with a 5σ significance a flux of $\sim$0.5 Crab per year.

2 Interaction of Very High and low energy photons

A limitation to γ-ray observations in the Very High Energy (VHE) range is the possible interaction of these photons with the extragalactic background radiation. A VHE photon of energy $E(z) = (1+z)E$ interacting with a background soft photon of lower energy $\epsilon(z) = (1+z)\epsilon$ at a distance corresponding to the redshift z, where E and ϵ are the presently observed ($z = 0$) photon energies, produces an electron-positron pair provided that [4]:

$$\epsilon > \epsilon_{min} = \frac{2(m_e c^2)^2}{E(1-\cos\theta)(1+z)^2} \tag{1}$$

where θ is the angle between the directions of the two photons. The interaction cross section is maximized when $\epsilon \approx 2\epsilon_{min}$. This means that TeV photons interact mainly with IR photons.

The effect of this photon-photon interaction modifies the typical high energy γ-ray spectra, which follow a power law $F(E) = K(E/E_0)^{-\Gamma}$, where Γ is the differential photon index, K a normalization constant and E_0 the normalization energy. The photon-photon absorption produces an exponential

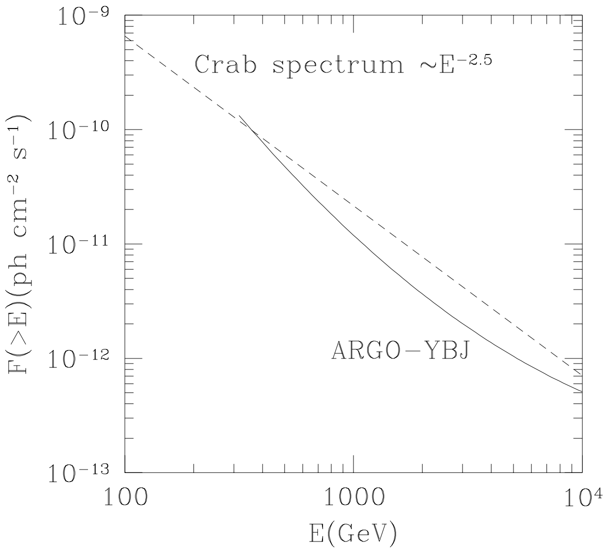

Figure 1: *5σ sensitivity of the ARGO− YBJ particle shower detector in 1 year observation time (solid curve), compared with the Crab Nebula power law spectrum (dashed line) determined with the Whipple Observatory* [3].

cut-off giving a spectrum of the form $F(E) = KE^{-\Gamma}\exp(-\tau(E,z))$, where $\tau(E,z)$ is the optical depth given by [5]:

$$\tau(E,z) = \frac{c}{2H_0}\int_0^z dz' \frac{(1+z')}{(1+\Omega z')^{1/2}} \int_0^{\pi} (1-\cos\theta)\sin\theta d\theta \int_{\epsilon_{min}}^{\infty} n(\epsilon)\sigma(E,\epsilon,\theta,z')d\epsilon \tag{2}$$

where z is the redshift of the γ-ray emitting source, Ω the cosmological density parameter, and $n(\epsilon)$ the number density of cosmic background photons per unit energy. The Hubble constant H_0 has been taken here to be 65 $km\ s^{-1}$ Mpc^{-1}. This expression for the optical depth is valid in the case that all background photons are in place at the time of redshift z. Therefore, the study of the interaction of VHE γ-rays with low energy photon fields requires the determination of the optical depth $\tau(E,z)$.

The totality of the intergalactic radiation fields which interact with photons detectable by ARGO−YBJ is referred to as the Extragalactic Background Light (EBL). Unfortunately, foreground emissions make difficult the observational determination of the EBL, particularly in the mid-IR wavelength range.

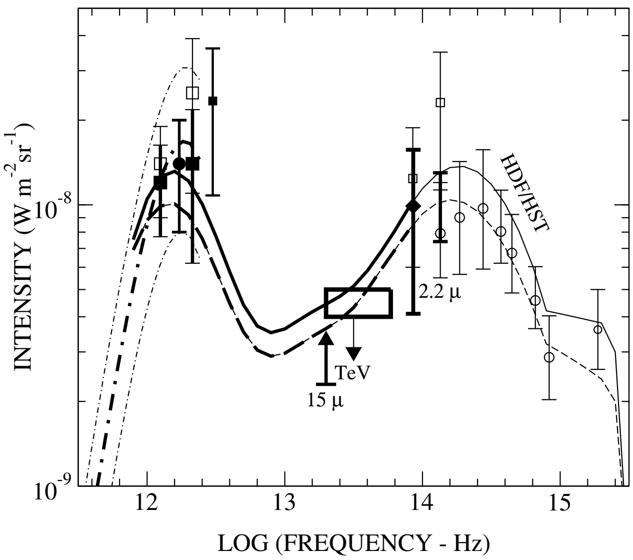

Figure 2: *The SED of the EBL* [6]*. Together with observationally derived values (error bars are given at the* $\pm 2\sigma$ *level), an empirical model* [7] *is shown both in its baseline (thick dashed line between* $\log \nu$*=11.8 and 13.8) and fast evolution form (thick solid curve over the same frequency range). The thick box marked "TeV" represents the TeV* γ*-ray-based upper limits.*

However, empirical models based on indirect observations have been also proposed. The current knowledge of the EBL is summarized in fig.2. The Spectral Energy Distribution (SED) is characterized by a stellar optical peak, a far-IR dust emission peak, and a mid-IR valley which allows for some warm dust emission. Different models, as that shown in fig.2, predict rather flat SEDs in the mid-IR range with average flux levels of 3−4 nW m^{-2} sr^{-1}. These flux levels are consistent with the indirect constraints [8] based on the pair-production process described above and indicated by the box in fig.2.

The empirical model reported in fig.2 has been later extended into the optical range by a hybrid model [6] (see thin dashed and solid curves) and parameterized with a fourth order polynomial, which approximates $\tau(E, z)$ correctly within 5% for all values of $z < 0.3$ and $0.1 < E_{TeV} < 50$. With this parametric expression for the optical depth to high energy γ-rays we can evaluate the flux absorption amount at different energies and redshifts, and study its effect on intrinsic source spectra.

3 High energy γ-ray emission from blazars

The current paradigm for Active Galactic Nuclei (AGNs) includes a central engine, probably a massive black hole, surrounded by an accretion disk and by fast-moving clouds, under the influence of a strong gravitational field, emitting Doppler-broadened lines (more distant clouds emit narrower lines). Absorbing material, distributed with a toroidal shape, obscures the central parts so that for transverse lines of sight only the narrow-line emitting clouds are seen. In radio-loud objects we have the additional presence of a relativistic jet, roughly perpendicular to the accretion disk. This produces strong anisotropy and amplification of the continuum emission (*i.e.*, relativistic beaming, bulk relativistic motion of emitting plasma) when viewed face-on. Within this scheme, blazars represent the fraction of radio-loud AGNs with their jets at relatively small ($\leq 20{-}30°$) angles with respect to the line of sight [9].

Given that these relativistic jets are relatively narrow, it is unlikely that our line of sight will intercept one of them. This, together with the fact that radio-loud sources constitute only $\sim 10\%$ of AGNs, implies that blazars represent a rare class of objects. As a consequence, our understanding of the blazar phenomenon is mostly based on a relatively small sample of high luminosity sources.

The blazar class includes Flat Spectrum Radio Quasars (FSRQs) and BL Lacertae type objects (BL Lacs). These are thought to be the "beamed" counterparts of high and low luminosity radio galaxies, respectively. The main difference between them lies in their emission lines, which are strong for FSRQs and weak (or absent) in BL Lacs.

More than 60 γ-ray sources detected, up to energies of $\simeq 5$ GeV, by the EGRET instrument on-board the Compton Gamma Ray Observatory (CGRO) satellite, have been identified [10] with objects belonging to this class of AGNs, with a differential photon index varying in the range $\Gamma \sim 1.4{-}2.6$.

A schematic view of the average SED of the different blazar subclasses, represented in terms of arbitrary units for the energy density $\nu L(\nu)$, where $L(\nu)$ is the monochromatic luminosity at frequency ν, is shown in fig.3. The favourite emission mechanisms suggested so far to explain the SED of blazars, characterized by two broad peaks at IR-optical-UV and MeV-GeV energies

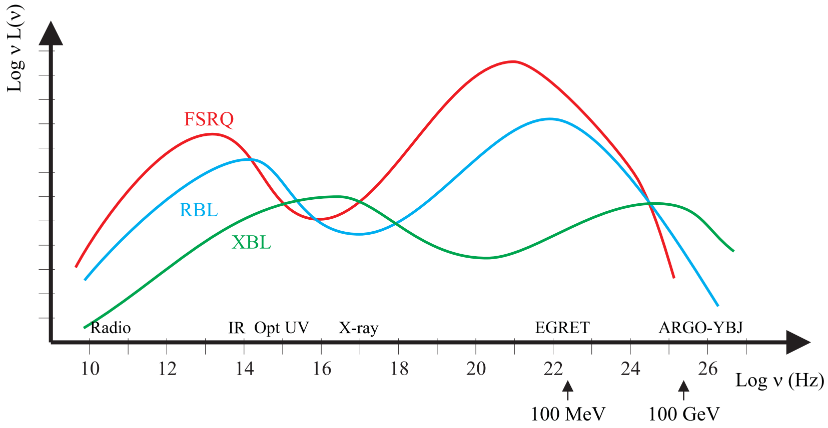

Figure 3: *Schematic average SED of different blazar subclasses from radio through TeV γ-rays. FSRQ indicates Flat Spectrum Radio Quasars, while RBL and XBL indicate respectively Radio-selected and X-ray-selected BL Lacs. The low energy component is probably due to synchrotron radiation and the high energy component to inverse Compton scattering. Also shown are the EGRET and ARGO−YBJ operation energy ranges.*

respectively, are synchrotron radiation from the electrons of the relativistic jet for the low frequency peak and inverse Compton scattering for the high frequency peak. Analysis of the SED of γ-ray blazars observed so far has shown that BL Lacs present higher energy peaks with respect to FSRQs. In particular, following the classification [11] of Radio-selected and X-ray-selected BL Lacs (respectively, RBL and XBL), these latter seem to be the blazars with SED shifted to the highest energies. Indeed, the four confirmed extragalactic VHE sources so far, namely Mrk 421 [12], Mrk 501 [13], H1426+428 [14], and 1ES 1959+650 [15], are all classified as XBL. In searching for the best candidate high energy γ-ray blazars, we will then look mainly at the XBL type.

4 Cosmological horizon for blazar observations with ARGO−YBJ

Now, exploiting the parametric expression for the optical depth $\tau(E, z)$ to high energy γ-rays (see §2), we can evaluate the flux absorption amount at different energies and redshifts, and study its effect on intrinsic blazar spectra. In the upper panel of fig.4 I report the flux attenuation due to photon-photon pair production at four redshift values increasing up to $z = 0.129$, which is the redshift of the farthest XBL observed so far in the VHE range,*i.e.*, H1426+428.

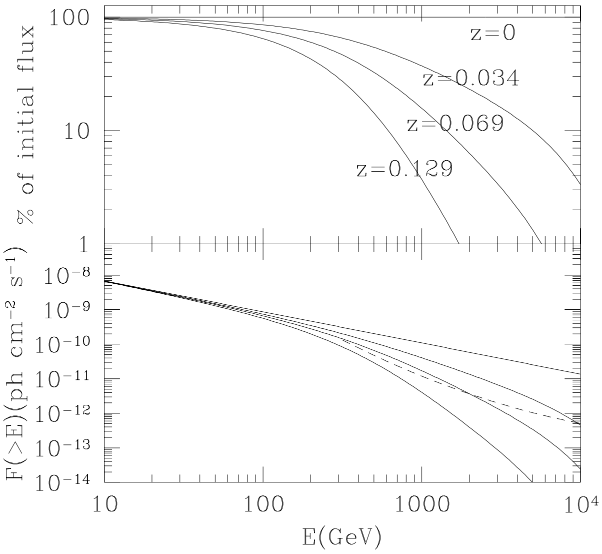

Figure 4: *Percentage of VHE photons reaching the observer after absorption by the EBL at different redshift values z (top), and effect of this absorption on the intrinsic* Γ*=1.9 power law spectrum of H1426+428 shifted at the same increasing z values (bottom). The dashed curve represents the ARGO−YBJ 5*σ *sensitivity in 1 year observation time.*

It is evident how the flux absorption increases with z. Reversing the argument, it is possible to obtain the unabsorbed spectrum of an observed VHE blazar. In the case of H1426+428, two different initial power law indices have been found by considering different data sets [14) 16)], respectively, Γ=1.9 and Γ=1.4. In the lower panel of fig.4 the effect of the photon-photon absorption on the intrinsic Γ=1.9 power law spectrum of H1426+428 is shown for the same increasing redshift values. The ARGO−YBJ 5σ sensitivity (dashed curve) limits the redshift at which it is possible to detect a γ-ray source with such a spectrum to a value $z \sim 0.1$.

Moreover, it must be taken in mind that blazars are characterized by a rapid flux variability, down to the hour time scale. In order to study such kind of variability a detector with sufficiently low exposure times is necessary. The ARGO−YBJ 5σ sensitivity, reported both in fig.1 and fig.4, is valid for 1 year observation time. This seems to be too long for the detection of flaring objects or variability studies. However, the definition of the signal-to-noise

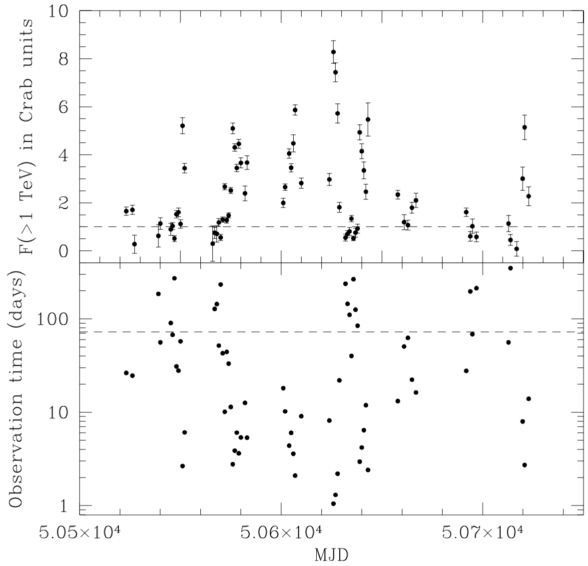

Figure 5: *Daily integral fluxes for the 1997 Mrk 501 outburst as seen by HEGRA, normalized to Crab flux (top), and corresponding expected observation times t_{obs} to achieve a 4σ detection with ARGO−YBJ (bottom). The dashed lines refer to the Crab.*

ratio implies that the observation time t_{obs}, the significance n_σ and the photon integral flux $F_\gamma(>E)$ of a signal are related by:

$$t_{obs} \propto \left(\frac{n_\sigma}{F_\gamma(>E)}\right)^2 \tag{3}$$

In order to evaluate the ARGO−YBJ capabilities for variability studies, we considered the 1997 outburst of Mrk 501. Taking the daily data collected by the stereoscopic HEGRA air Cherenkov Telescope during the period March to October 1997 [17], we calculated the expected observation times t_{obs} for a 4σ detection by ARGO−YBJ. These are shown in fig.5. As it can be seen, the observation time for the Crab is ∼70 days while in the favourable cases of sources flaring up to 7−8 Crab fluxes, ∼1 day of exposure is sufficient for a 4σ detection.

Considering all the above results, in order to find the upper z value at which it should be possible to detect γ-ray blazars with ARGO−YBJ, we first took as a standard candle the Crab Nebula spectrum determined with the

Table 1: *Catalogue of ARGO−YBJ (-10^o < δ <70^o) blazar candidates out to z=0.1*

Source	z	Type	Source	z	Type
0010+106	0.090	FSRQ	1404+286	0.077	FSRQ
0018+298	0.100	XBL	1413+436	0.090	FSRQ
0033+595	0.086	XBL	1532+303	0.067	XBL
0110+418	0.096	XBL	1610+671	0.067	XBL
0138+398	0.080	FSRQ	Mrk 501	0.034	XBL
0152+018	0.08	XBL	1727+502	0.055	XBL
0156+150	0.08	XBL	1741+196	0.083	XBL
0214+517	0.049	XBL	1807+698	0.051	RBL
0314+247	0.054	XBL	1959+650	0.048	XBL
0321+33	0.062	FSRQ	BL Lacertae	0.069	RBL
0430+052	0.033	FSRQ	2209+184	0.070	FSRQ
0656+426	0.059	XBL	2321+419	0.059	XBL
Mrk 421	0.031	XBL	2322+346	0.098	XBL
1349+281	0.0755	XBL	2344+514	0.044	XBL

Whipple Observatory [3]. Then, admitting VHE emissions with fluxes up to 7−8 Crab units, and varying the normalization constant K and the photon spectral index Γ, we obtained a cosmological horizon for blazar observations with ARGO−YBJ of z$\sim$0.1. The coincidence of this limit value with that obtained considering the spectrum of H1426+428 is consistent with the extreme features of the latter XBL [18]. Indeed, this source was monitored over several years by Cherenkov telescopes because of its high synchrotron peak energy (>100 keV).

5 Blazar candidates for ARGO−YBJ

In conclusion, having fixed a cosmological horizon and taking into account the ARGO−YBJ site latitude, it is possible to select the blazar candidates for ARGO−YBJ observations,*i.e.*, mainly XBL with $z \leq 0.1$ and declination $-10^o < \delta < 70^o$. Their list is presented in tab.1. However, lists such as tab.1 should not be considered as definitive for future TeV surveys. Since every time a large-area survey is done in a new waveband, some completely unexpected discovery is made, ARGO−YBJ has also a great discovery potential.

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