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Prospect on intergalactic magnetic field measurements with gamma-ray instruments

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Abstract. Observing high-energy gamma-rays from Active Galactic Nuclei (AGN) offers a unique potential to probe extremely tiny values of the intergalactic magnetic field (IGMF), a long standing question of astrophysics, astroparticle physics and cosmology. Very high energy (VHE) photons from blazars propagating along the line of sight interact with the extragalactic background light (EBL) and produce e^+e^- pairs. Through inverse-Compton interaction, mainly on the cosmic microwave background (CMB), these pairs generate secondary GeV-TeV components accompanying the primary VHE signal. Such secondary components would be detected in the gamma-ray range as delayed "pair echos" for very weak IGMF ($B < 10^{-16} G$), while they should result in a spatially extended gamma-ray emission around the source for higher IGMF values ($B > 10^{-16} G$). Coordinated observations with space (i.e. Fermi) and ground-based gamma-ray instruments, such as the present Cherenkov experiments H.E.S.S., MAGIC and VERITAS, the future Cherenkov Telescope Array (CTA) Observatory, and the wide-field detectors such as HAWC and LHAASO, should allow to analyze and finally detect such echos, extended emission or pair halos, and to further characterize the IGMF.

Keywords. magnetic field, intergalactic space, gamma-ray astronomy, pair echos, pair halos, high-redshift blazars

1. Introduction

The intergalactic magnetic field refers to a widespread cosmic magnetic field, permeating intergalactic voids (bubbles of about 100 Mpc), outside clusters of galaxies and filaments. The true existence of such an elusive field is not yet fully demonstrated, nor its main properties. In the limit of infinite conductivity of astrophysical plasmas, frozen-in magnetic fields roughly evolve as $\sim \rho^{2/3}$ or $\sim V^{-2/3}$ where ρ and V are the density and volume of the related plasma. Any cosmological magnetic field is significantly diluted during the expansion of the universe, while amplified by gravitational collapse, making it difficult to identify a pure IGMF component.

Still recently, extragalactic magnetic fields of the order of the μG on typical scales of tens of kpc have been firmly detected only in the intracluster medium, especially in a number of rich clusters, through the observation of their synchrotron and Inverse-Compton emission in the radio and the X-ray ranges and of Faraday rotation measures from high-redshift radiosources (Ryu *et al.* (2012)). Magnetic fields up to a few tens of μG have been detected in cooling flows like in the Hydra cluster (Kronberg (1994)). Recent promising scenarios for the generation of such 10 μG-field consider galactic mergers driving cluster-scale dynamos. On the larger supercluster scale, solely hints of a few 0.1 μG magnetic fields have been reported in bridges, filaments and shock waves, with a coherence scale of a few Mpc as discussed by Kim (1989), Ensslin (2001), Xu (2006), Kronberg (2007), Ensslin *et al.* (2009), Beck (2009) and Bruggen *et al.* (2012). However, standard detection methods remain up to now unable to get firm detections of a magnetic field in intergalactic voids, namely an IGMF not related to any gravitational collapse, possibly existing prior to galaxy formation, and coherent on scales larger than known structures in the cosmos (Widrow (2002)).

Here we discuss an alternative method to explore the IGMF which has recently proved to be promising by Neronov & Vovk (2010) and Aleksic *et al.* (2010). The idea is to consider the cascades of secondary particles generated by very high energy gamma-rays during their propagation from remote AGN to the Earth and the subsequent deflection of the charged particles by any non zero IGMF. Although still model-dependent, such an approach allows at the moment to put lower bounds on the IGMF and provides the first signature of a non zero large scale cosmic magnetic field. The improved performances of the next generation of gamma-ray instruments should firmly characterize the IGMF, revealing its nature and the origin of magnetic field in galaxies and galaxy clusters.

2. The Intergalactic Magnetic Field

Depending on its origin, the actual detection of a non zero IGMF could shed new light on the early universe and complete the dynamo description for the origin of cosmic magnetic fields, especially by providing magnetic seed fields for dynamo amplification processes in turbulent flows during the formation of the large scale structure. Conversely, it could appear as an alternative to dynamo scenarios, and be especially useful to explain young magnetized large scale structures, with little time for dynamo growth, such as the magnetic bridge identified in the Coma supercluster.

Standard constraints on the IGMF fix various upper limits on the magnetic field value and mainly come from (1) the nucleosynthesis of light elements, (2) the CMB anisotropy, and (3) the Faraday rotation measures of radio-loud AGN. The great success of the theory on the Big Bang nucleosynthesis could be altered by the presence of any strong primordial magnetic field, mainly through the change of the expansion rate. This implies a strict upper limit on the IGMF of $B_{IG} < 10^{-6}$ G. The presence of an homogeneous magnetic

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field at decoupling ($z \sim 1100$) induces a different expansion in different directions and distorts the cosmic microwave background (CMB). The isotropy observed in the CMB data then imposes upper limits of $B_{IG} < 5 \times 10^{-9} h_{75} \Omega^{1/2}$ G over the horizon for a frozen magnetic field evolving as $\sim (1+z)^2$ and $B_{IG} < 10^{-8}$ G over the 10Mpc-scale (Barrow *et al.* (1997) and Durrer *et al.* (1998)). The interpretation of the Faraday rotation measures of AGN is model-dependent. Assuming an homogeneous magnetic field and plasma density across the Hubble volume, Vallée (1990) deduced an upper limit of $B_{IG} < 6 \times 10^{-12}$ G for a mean density of 10^{-5} cm^{-3}. For variations of the IGMF and of the density on scales much smaller than c/H_0, the variance of the rotation measures should increase with the redshift and be detectable for $B_{IG} \sim 6 \times 10^{-9}$ G (Kronberg & Perry (1982), Blasi *et al.* (1999)), which is not observed. A strict upper limit of $B_{IG} < 10^{-9}$ G can be deduced in such a case (Kronberg (1994)). However such limits need to be revisited with a more accurate description of the large scale structure and taking into account evolutionary effects in intrinsic rotation measures (Kronberg *et al.* (2008)).

There are various ways to generate the IGMF in the primordial universe. If there is no magnetic field at the very beginning, this requires to find a cosmological time and place where flux freezing is not valid to start the magnetic field. This can occur during or after the inflation. The inflation period is interesting to create the seed of the IGMF because quantum fluctuations can produce large scale phenomena from microphysical processes, and the low conductivity permits an increase of the magnetic flux. Electromagnetic quantum fluctuations amplified during inflation would appear now as a static IGMF, electric fields being screened later on, during the highly conducting plasma epoch (Grasso & Rubinstein (2001), Kandus *et al.* (2011)). A post-inflation generation of the IGMF is also possible, at the time of decoupling transitions of fundamental forces, where changes in the nature of particles and fields plus release of free energy induce electric currents and therefore magnetic fields. Small-scale primordial magnetic fields could be created in relation to the bubbles and shock fronts possibly expected during the quark-hadron phase transition or the electroweak phase transition (Grasso & Rubinstein (2001)).

However the scenarios presently available for a primordial magnetogenesis have to face two difficulties. Magnetic fields generated during inflation are very weak, and those generated during a phase transition tend to have very small scales. As a result, primordial magnetic fields might remain too weak or not sufficiently extended to induce a significant

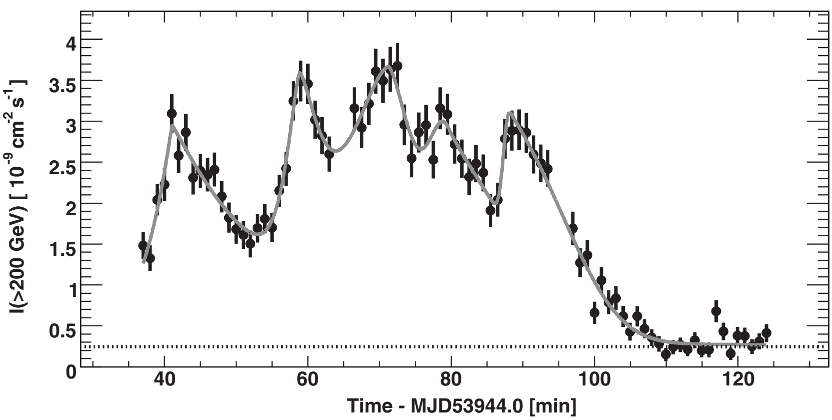

Figure 1. An example of fast variability observed during the first big flare in the VHE light curve of the blazar PKS 2155-304 at an epoch of highly active state in July 2006 (Aharonian *et al.* (2007)).

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IGMF and to serve as seed fields for the subsequent growth of galactic magnetic fields. In this regard, an astrophysical origin of the IGMF appears as an interesting alternative. A substantial IGMF could be formed later on by ejection of magnetized plasmas into the intergalactic space, from galaxies, AGN, starbursts, Pop III stars and large scale shocks, as discussed for instance by Kronberg (1994), Widrow *et al.* (2012), Ryu *et al.* (2012) and Lilly (2012).

For recent overviews on the primordial magnetic field and the IGMF, see for instance reviews by Widrow (2002), Kulsrud & Zweibel (2008), Kandus *et al.* (2011), Widrow *et al.* (2012) and Ryu *et al.* (2012).

3. High-redshift blazars as beacons of TeV gamma-rays

Present ground-based imaging atmospheric Cherenkov telescopes (ACT), H.E.S.S. in Namibia, MAGIC in the Canary Islands, and VERITAS in USA, have detected about 50 AGN at very high energies in the range 100 GeV - 30 TeV, up to redshift $z \sim 0.6$. The TeV AGN sample is still constantly increasing and the outlook is favorable with the entry into operation of the large telescope H.E.S.S 2 (28 m of diameter) in fall 2012. Apart from four radiogalaxies, the TeV population of AGN consists mainly of blazars, mostly highly variable sources which all appear point-like up to now. Blazars are radio-loud AGN with their jets orientated at small viewing angles towards the Earth. AGN light curves currently available at VHE show variations on all time scales, from years down to a few minutes as shown in Fig. 1. The VHE emission likely comes from the jet base and is believed to be due either to relativistic electrons which boost softer ambient

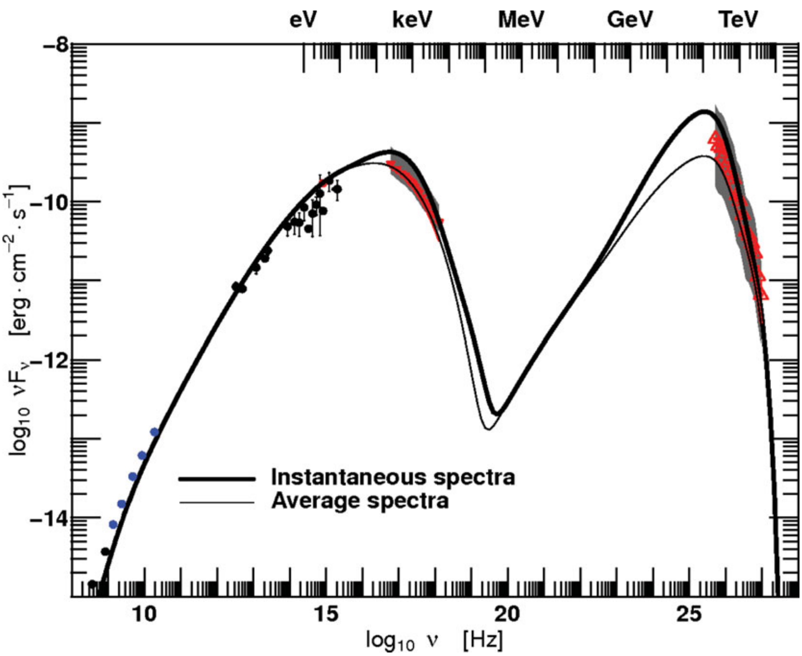

Figure 2. Spectral energy distributions (SED) of the blazar PKS 2155-304 during its 2006 highly active state. The highest activity level corresponds to the second big flare detected in the VHE light curve. Red points show nightly average spectra from Chandra and H.E.S.S. data, while the grey band indicates the varying Chandra and H.E.S.S. spectra. Thin and thick solid lines present time dependent synchrotron-self-Compton models able to reproduce the SED (from Aharonian *et al.* (2012)).

photons to the TeV range through inverse-Compton interaction, or to relativistic protons which can directly synchrotron radiate at VHE or create secondary pions which decay into TeV photons. Fig. 2 illustrates the typical shape of the spectral energy distribution from radio to TeV gamma-rays and the capability of time-dependent synchrotron-self-Compton models to fit the blazar spectra. Interestingly such variable gamma-ray beacons provide new ways to probe the space-time structure, intergalactic medium, extragalactic backgrounds and IGMF along their line of sight. The procedure should become more and more efficient with improved gamma-ray instruments performances.

4. Probing weak Intergalactic Magnetic Field with gamma-rays

Primary TeV photons from remote blazars interact with lower energy background radiation on their way to the Earth, especially with the EBL photons, and create electron-positron pairs through the process $\gamma_{\mathrm{VHE},1} + \gamma_{\mathrm{IR}(EBL)} \rightarrow e_1^+ e_1^-$. These electrons and positrons in turn interact mostly with photons of the CMB and generate secondary gamma-ray photons by inverse-Compton effect $e_1^- + \gamma_{\mathrm{IR}(CMB)} \rightarrow \gamma_{\mathrm{VHE},2} + e_2^-$. This second generation of gamma-rays again interact with the EBL. As illustrated in Fig. 3, the whole process results in the development of an electromagnetic cascade and the production of secondary GeV components whose characteristics strongly depend on the properties of the IGMF which affects the trajectories of the charged particles and deflects the pairs. Such secondary components could appear as an "echo", namely a GeV radiation delayed in time relatively to a variable primary TeV signal for tiny IGMF below 10^{-16} G, or as an extended emission around the primary TeV signal for higher IGMF values. These two effects were first proposed respectively by Plaga (1995) and Aharonian *et al.* (1994). The actual detection of delayed secondary GeV gamma-ray pulse could in principle bring to light the existence of an IGMF down to 10^{-24} G. Conversely, as initially analyzed, physical "pair halos" around the primary sources are formed when velocities of the pairs are isotropized by a sufficiently strong magnetic field ($B_{IG} \leqslant 10^{-12}$ G) within ~ 10 Mpc of the sources. Fig. 4 shows the appearance that could have a typical pair halo, for an intermediate value of the IGMF. Other examples of virtual images of pair halos around AGN can be found for instance in Elyiv *et al.* (2009) and various simulations of pair echos in Taylor *et al.* (2011).

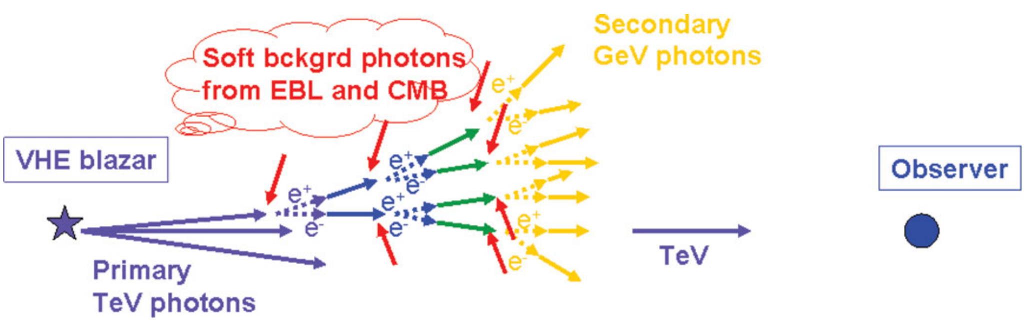

Figure 3. Sketch of the development of a cascade of electron-positron pair creation along the line of sight of a VHE blazar. TeV gamma-rays from the blazar mostly interact with the EBL and produce e^+e^- pairs which in turn Compton upscatter CMB photons into the gamma-ray range. Such cascading effect results in the creation of secondary GeV-TeV components, somewhat delayed and extended compared to the primary VHE signal, which could be detected as pair "echos" or "halos" by gamma-ray instruments.

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5. Current attempts of VHE extension and echos detection

The current era is very propitious to the study of extension, halos and echos at high and very high energies, thanks to the large spectral range covered in gamma-rays with the simultaneous exploitation of the Fermi satellite around GeV energies and of the ground-based atmospheric Cherenkov telescopes around TeV energies.

However, up to now, the search for any signature of extended emission due to pair creation around blazars has been severely limited by the sensitivity of gamma-ray detectors and mostly results in upper limits (see for instance Aleksic *et al.* (2010)). One first tentative report of halo detection in the stacked images of the 170 brightest AGN of the Fermi 11-months catalogue has been announced, combining data from Fermi in the GeV band and from ACT in the TeV band. Size and brightness were found consistent with $B_{IG} \sim 10^{-15}$ G (Ando & Kusenko (2010)). Nevertheless that signature stands out only at 3.5σ and was not confirmed. It still remains questionable taking into account the complexity of possible instrumental effects.

Regarding the search of echos, the usual non-detection of secondary cascade components provides for the first time lower limits on the value of B_{IG}, if one assumes that the suppression of the secondary components is due to the deflection of the e^+e^- pairs by the IGMF. Modeling the development of the cascades with Monte Carlo simulations, Taylor *et al.* (2011) derive such type of constraints from simultaneous data obtained by Fermi and by ACT on three blazars. The measured GeV fluxes being lower than the fluxes expected from the simulated cascades imply, assuming a correlation length larger than 1 Mpc for the IGMF and a persistent TeV emission over long timescales, a lower limit of $B_{IG} > 10^{-15}$ G if the dimming of the cascade emission is due to spatial extension, and of $B_{IG} > 10^{-17}$ G if it is due to time delay. A rather similar analysis conducted

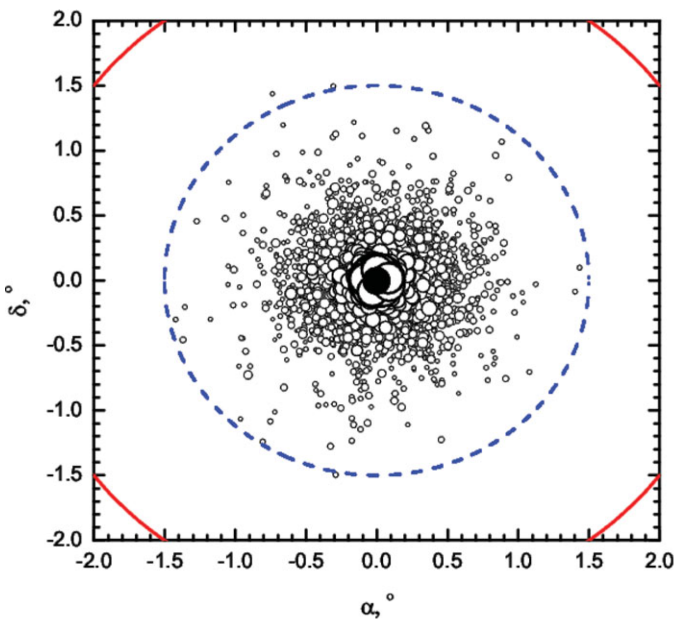

Figure 4. Expected geometry and spectral distribution of a pair halo from a blazar at a distance of 120 Mpc with a high energy cut-off of ~ 300 TeV, for an IGMF value of 10^{-15} G. The large blue and red circles mark the fields of view of radii 1.5 and 2.5 degrees on the sky. The small black circles correspond to the arrival directions of the primary and secondary gamma-rays, their size being proportional to the photon energy (from Elyiv *et al.* (2009)).

by Essey *et al.* (2011) concludes to the same typical values, depending on the scenario adopted for the EBL. In the case where blazars emit both gamma-rays and cosmic rays, secondary cascade photons can dominate the observed spectrum and both upper and lower limits can be deduced for the IGMF, namely $10^{-17} < B_{IG} < 3 \times 10^{-14}$ G. These limiting values are clearly model-dependent. Releasing or modifying some of the assumptions, as the one of persistent TeV emission, results in smaller lower limits on the IGMF (Dermer *et al.* (2011)), but the conclusion of a non-zero IGMF remains robust in a large variety of models (Dolag *et al.* (2011), Takahashi *et al.* (2011)). A somewhat different approach by Neronov *et al.* (2012) analyzes a recent strong orphan TeV flare of Mrk 501, with no activity below 10 GeV but for which a Fermi counterpart has been found in the 30–300 GeV band. Modeling such GeV-TeV flare by an electron-positron pair cascade initiated by 100 TeV primary gamma-rays again appears consistent with an IGMF of the order of $10^{-16} - 10^{-17}$ G for a correlation length above 1 Mpc.

To summarize, present-day results of the GeV and TeV gamma-ray astronomy all conclude to the existence of a non-zero IGMF. Nonetheless, they are merely based on the non-detection of expected secondary gamma-ray signals, and are not yet able to really determine the IGMF properties in terms of strength, degree of homogeneity, filling factor, origin. Moreover, additional effects in the intergalactic space could drastically modify the global description of the development of the cascades, if energy losses other than Inverse-Compton scattering affect them. This may be the case for instance if plasma-beam instabilities, which can dissipate locally the energy of pairs, efficiently grow on timescale shorter than the inverse-Compton cooling rate as proposed by Broderick *et al.* (2012). This could question the validity of lower limits deduced from the non-detection of GeV secondary components, but requires a deeper analysis, especially concerning the non-linear evolution of the instabilities. Only positive detections with detailed data on the cascade signatures will allow to disentangle the various effects and will open new paths to characterize the IGMF and the extragalactic backgrounds.

6. Prospect with future gamma-ray instruments

This decade should see the advent of various new gamma-ray detectors at VHE, especially the LHAASO, HAWC and CTA. The two first ones are wide-field instruments with a high duty cycle, which should provide regular and long-term coverage of the variable multi-TeV emission of blazars. High quality VHE lightcurves over years will be mandatory to better constrain the primary photons and the cascade development. LHAASO is a project of Large High Altitude Air Shower Observatory in Tibet, with multiple detection methods of gamma-rays and cosmic rays (see Fig. 5). HAWC, the High Altitude Water Cherenkov gamma-ray observatory in Mexico, will also detect gamma-rays and cosmic rays in the 100 GeV - 100 TeV range. With a large field of view of 15% of the sky, it will

Figure 5. Virtual image of the Large High Altitude Air Shower Observatory (LHAASO) project in Tibet.

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Figure 6. Picture of the High Altitude Water Cherenkov (HAWC) observatory in Mexico.

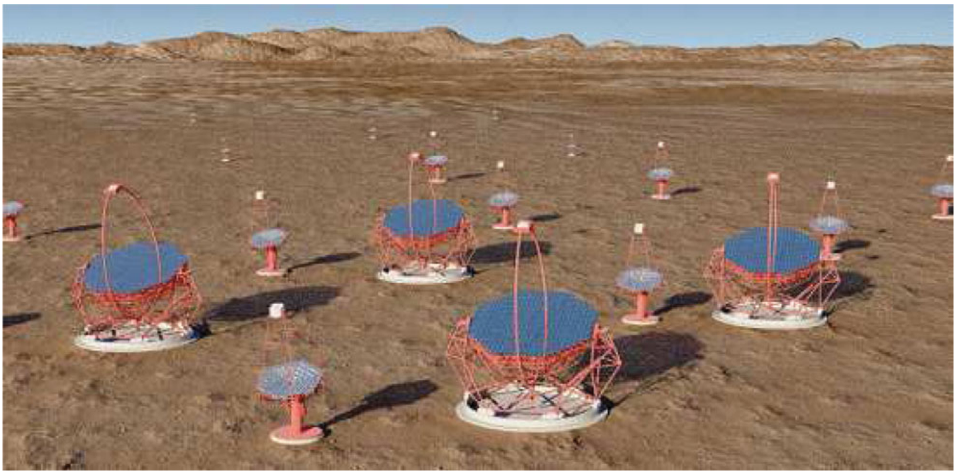

Figure 7. Virtual image of the future Cherenkov Telescope Array showing large (LST), medium (MST) and small size (SST) telescopes. One possible configuration for the southern array consists in a low-energy section above a few tens of GeV with four 23 m parabolic telescopes, a core-energy array with twenty-three 12 m Davies-Cotton telescopes in the range 100 GeV to 10 TeV, and a high-energy section with thirty-two 4-6 m Davies-Cotton or Schwarzschild-Couder telescopes at multi TeV energies.

Table 1. Overview of the average performance goals of CTA

Differential sensitivity	Field of view	Angular resolution	Energy resolution	Astrometric accuracy
$2 \times 10^{-13} erg\ cm^{-2} s^{-1}$ at 1 TeV	$8°$ at 1 TeV	$\leqslant 3'$ above 1 TeV	$\leqslant 10$ % above 1 TeV	$\sim 6''$ at 1 TeV

cover half the sky in one day. An array of particle counters is already under construction at an altitude of 4100 m (see Fig. 6).

CTA, the Cherenkov Telescope Array, is the next generation project of imaging atmospheric Cherenkov telescopes (Actis *et al.* (2011)). It will consist of several tens of

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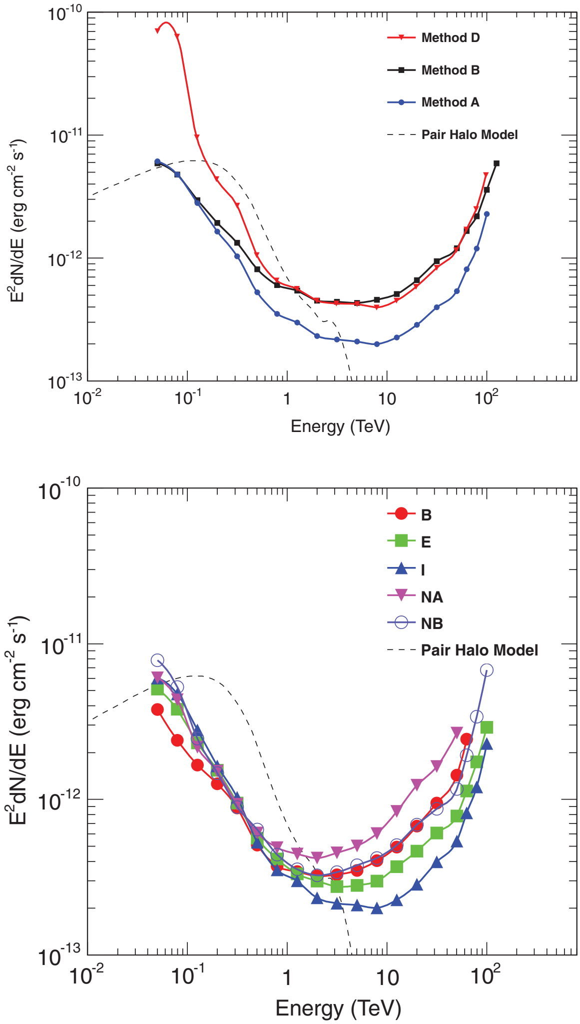

Figure 8. Sensitivity of CTA and flux estimates on the expected pair halo emission. A differential angular distribution of a pair halo at $z = 0.129$ (like the blazar 1ES1426+482) and $E_\gamma > 100$ GeV was used as theoretical model (dashed line), from Eungwanichayapant & Aharonian (2009). An intermediate value of the IGMF is assumed, as well as a monoenergetic distribution of the primaries at 100 TeV and a luminosity of 10^{45} erg/s. In the upper panel, the sensitivity of the CTA array in configuration I to pair halo emission is shown for three different analysis methods to search for the extension. The flux quoted is that within a 1° region of the source. In the lower panel, flux estimates are given for various CTA array configurations (50 hours observing time for each field, 20 degrees zenith angle observations), for the analysis method A (see text).

Cherenkov telescopes of various sizes (see Fig. 7). An overview of the performance goals of CTA is given in Table 1. Compared to present ACT, CTA should increase by an order of magnitude the sensitivity at TeV energies, reaching the milliCrab level, and significantly broaden the effective energy coverage from a few tens of GeV up to hundreds of TeV. The angular resolution will be improved down to the arcminute scale. Large fields of view, between 5 to 10 degrees for the various telescopes, and the construction of two arrays in the southern and in the northern hemispheres, will ensure a good sky coverage over years. The two sites should be selected before 2014. CTA will be operated as

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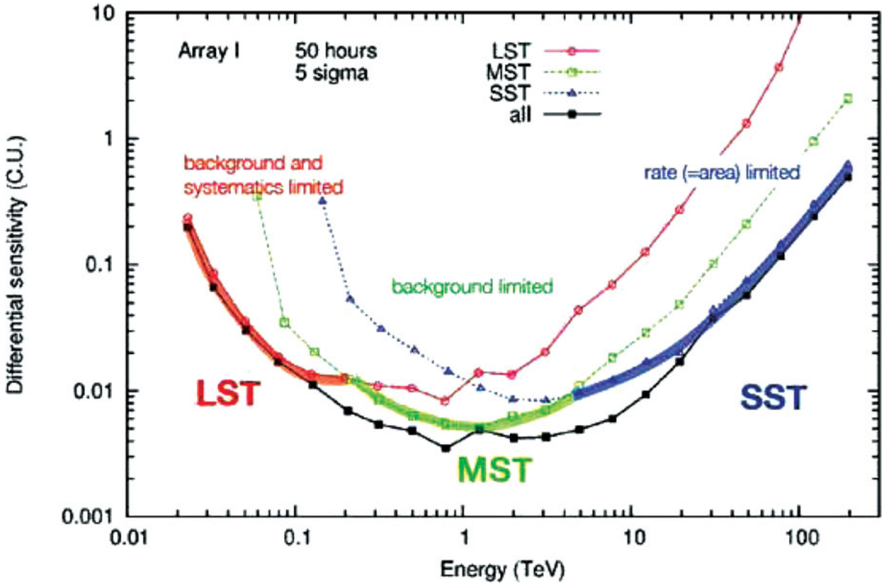

Figure 9. The differential sensitivity of CTA configuration "I" and of its LST, MST and SST sub-arrays, showing how the telescopes of different size allow to cover a large spectral range from a few tens of GeV to above 100 TeV (from Bernlohr *et al.* (2012)).

an observatory open to the whole scientific community, offering a multi-functional tool with several configurations and observation modes. A lifetime of about 30 years can be anticipated.

As shown in Fig. 4, typical pair halos fit well into the field of view of CTA telescopes, which should allow for reliable background subtraction. The expected sensitivity for pair halo detection with CTA has been calculated with three different methods illustrated in Fig. 8. Methods A and B rely on a 5 σ excess above the expected background. Method A searches for some overall extended emission with a halo profile for $\theta < 0.32°$. Method B probes a region in which a point-like central source would no longer be dominant ($0.11° < \theta < 0.32°$) and therefore provides the most basic method of establishing the detection of extended emission. For method D the "goodness of fit" for a halo profile (convolved with the CTA PSF) fitted to simulated CTA data is used to determine the expected flux sensitivity. Method D tests how well a point-like source and a pair halo can be distinguished. This is done by assessing the difference between the likelihood obtained for a PSF hypothesis and that obtained for a pair halo function, with the limiting flux defined as that at which the point-source hypothesis can be rejected at the 5 σ level. The rather high flux sensitivities for Methods B and D in Fig. 8 indicate the difficulty of identifying halo-like emission at this confidence level. However a potentially extended source detected at the sensitivity limit with a significance of 5 σ would be distinguished from a point source with about 95% confidence (see Sol *et al.* (2012) for more details). Fig. 8 also shows the pair halo sensitivity derived with method A for various CTA candidate configurations which are presently under study to optimize the final array performances. Configuration I appears to be the most suitable setup for pair halo studies. It corresponds to a mixed array consisting of 56 SST, 18 MST and 3 LST with field of view of 9, 8 and 4.9 degrees respectively, providing a balanced sensitivity over a large energy range as shown in Fig. 9.

7. Conclusion

During the last decade, the advent of a new branch of astronomy at very high energies has offered several spectacular discoveries by ground-based experiments on different types of cosmic sources, connected to most areas of contemporary astrophysics. The next generation of instruments will help to deepen the exploration of the gamma-ray universe and has a great potential for research in astrophysics, cosmology and fundamental physics, including, to name a few, the study of the origin of cosmic-rays, the investigation of cosmic particle accelerators, the exploration of black holes physics, the search for dark matter and exotic effects. Somewhat unexpectedly, this new way to investigate the cosmos offers the great benefit to probe in depth the lines of sight of remote VHE gamma-ray sources and to possibly access observational signatures of extremely tiny magnetic fields permeating the cosmos on the largest scales in the intergalactic space. This gamma-ray method might reach intergalactic magnetic fields weaker by more than 10 orders of magnitude than the range of fields detectable by other means. The advent of new instruments as LHAASO, HAWC and CTA might open a new era for IGMF studies. For this purpose, it will be important to ensure that gamma-ray instruments, as the Fermi satellite and its potential successors, are simultaneously operating in space to provide a complete coverage of the large gamma-ray spectral range and optimize the constraints on long-term lightcurves and spectra. This should help to clarify the strength, properties and origin of the IGMF, and to recognize the relative importance of the primordial magnetogenesis and the amplification of magnetic field by turbulent flows during the formation of large scale structures.

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