PROCEEDINGS OF SCIENCE

The Sub-TeV transient Gamma-Ray sky: challenges and opportunities

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The detections of γ-ray sources coincident with a Gravitational Wave event and an ultra-energetic neutrino officially started the era of multi-messenger astrophysics. These two ground-breaking announcements demonstrated that monitoring the sky in γ rays will be fundamental to identify the electromagnetic counterpart of transient events and promptly trigger follow-up observations, aiming at the full characterization of the signal.

In recent times, our ability to study high-energy γ rays greatly improved, particularly through the use Imaging Atmospheric Cherenkov Telescopes (IACTs), which will reach unprecedented performance with the Cherenkov Telescope Array (CTA). These instruments, however, have limited duty cycle and field of view, lowering their efficiency in the observation of transients, if not properly alerted. Extensive Air Shower (EAS) arrays, on the contrary, can survey large areas of the sky and provide prompt information on high-energy transients, working in combination with other observatories. Here, we present the Southern Wide field of view Gamma-ray Observatory (SWGO), a new EAS facility designed to monitor the Southern sky, from $\delta \simeq +27^{\mathrm{o}}$ down to approximately -73^{o}. We describe the issues that such an observatory needs to address to operate down to the sub-TeV energy range, and the advantages that would result from their solution.

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1. Introduction

The detection of γ-ray emission in coincidence with a gravitational wave event (GW170817, [1, 2]) and with an ultra-energetic IceCube neutrino (IceCube-170922A, [13]) clearly demonstrated that observations of the sky in High Energy (HE, $E \geq 10\,\mathrm{GeV}$) and Very High Energy γ rays (VHE, $E \geq 100\,\mathrm{GeV}$) will play a key role in the development of multi-messenger astrophysics. The analysis of this radiation with space instruments, such as the Fermi Large Area Telescope (LAT, [9]), and ground based Imaging Atmospheric Cherenkov Telescopes (IACTs), like MAGIC, H.E.S.S. and VERITAS [7, 4, 12], led to associate its origin with the most extreme astrophysical environments. If, on the one hand, a relevant fraction of VHE emission comes from a diffuse component, well interpreted as the result of the interaction of ultra-energetic cosmic-ray particles with the interstellar medium of the Galaxy (ISM), on the other, point-like sources can be generally associated with neutron stars, SuperNova Remnants (SNR), Gamma-Ray Burts (GRB) and Active Galactic Nuclei (AGN), particularly blazars. As a result, the VHE radiation spectrum is intimately connected with the acceleration sites of relativistic charged particles from the Milky Way and beyond [14], as well as with the cosmic distribution of accelerators and the opacity of the Universe through the pair production mechanism on Extragalactic Background Light (EBL, [10]).

Although the best performances, in terms of sensitivity and resolution towards the VHE domain, have been obtained by IACTs, which will soon reach unprecedented levels with the Cherenkov Telescope Array (CTA, [11]), the narrow field of view and the relatively low duty cycle of these instruments make them unsuitable to monitor large areas of the sky and to track fast transients, if their position is not accurately constrained by external triggers. Here, we describe the contribution that will be given by the Southern Wide field of view Gamma-ray Observatory (SWGO, [6])[1] in the field. SWGO is proposed as a new Extensive Air Shower array (EAS), which will operate in the southern hemisphere, providing the sensitivity and sky coverage illustrated in Fig. 1 and thereby compared with the distribution of different classes of VHE sources, as listed in the *TeVCat* online catalog[2] [15]. In the following sections, we describe which problems need to be addressed to achieve the required performances and the solution offered by SWGO. We conclude the discussion with an estimate of the contribution of SWGO on the expected detection rates of transient sources.

2. The sub-TeV challenge

Since most astrophysical sources have a VHE spectrum that can be roughly expressed in the form of a power-law:

$$\frac{\mathrm{d}N}{\mathrm{d}E} = N_0 \left(\frac{E}{E_0}\right)^{-\alpha} \quad [\mathrm{ph\ cm^{-2}\ s^{-1}\ GeV^{-1}}] \tag{2.1}$$

with the spectral index generally being $\alpha \geq 1.5$, it follows that their observation in the sub-TeV/TeV range requires detectors with large effective areas, which cannot be deployed in space. A viable alternative is the analysis of the electromagnetic air showers that are generated when the VHE photons interact with the atmosphere, producing relativistic charged particles and Cherenkov radiation.

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[1] https://www.swgo.org

[2] http://tevcat.uchicago.edu/

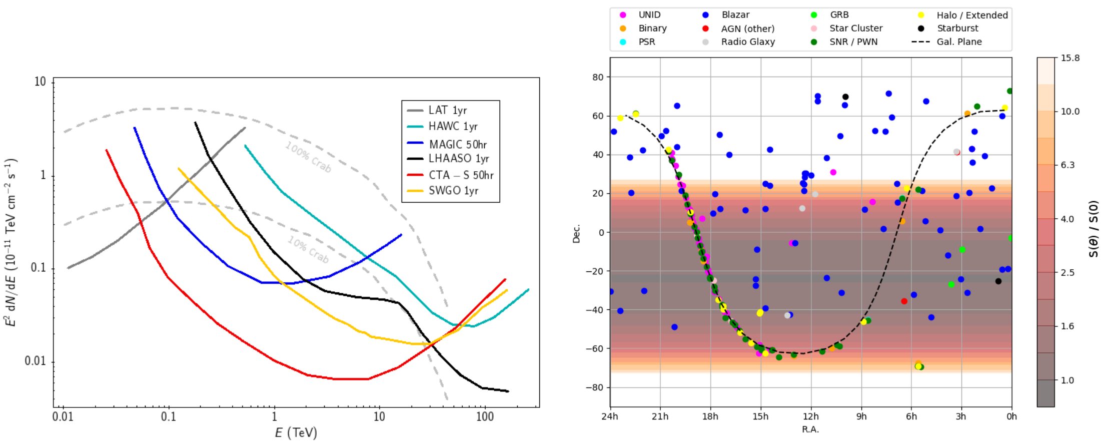

Figure 1: The sensitivity of SWGO [6, 8] compared with that of other observatories (left panel) and the field of view of the instrument, plotted together with the distribution of known TeV sources (right panel). The curves of the sensitivity plot are compared with the spectrum of a source producing 1 and 0.1 times the flux of the Crab Nebula, while the shading of the field of view represents the degradation of sensitivity as a function of zenith distance with respect to a source that culminates at the zenith of SWGO. The different source classes are represented by the symbols shown in legend.

Observing such showers on the ground, however, raises important problems, because the showers initiated by γ-ray photons with $E \leq 1\,\mathrm{TeV}$ can only propagate down to approximately 5000 m a.s.l., implying that the instruments need to operate at high altitude. In addition, γ-ray showers must be distinguished by the background of atmospheric cascades originated by cosmic rays. Since the cosmic-ray flux has an energy spectrum that is approximately described by:

$$\frac{\mathrm{d}N_E}{\mathrm{d}E} = 1.8 \left(\frac{E}{1\,\mathrm{GeV}} \right)^{-2.7} \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}, \tag{2.2}$$

assuming a spatial resolution element of 1 square degree, for a source with the Crab Nebula spectrum above 150 GeV, there is approximately 1 γ-ray shower for 160 background events. As a consequence, the possibility to reach the required performances critically depends on the characteristics of the observing site and on the efficiency of the background rejection procedures.

3. The contribution of SWGO

The SWGO Collaboration aims at deploying a large array of EAS detectors ($\sim 80000\,\mathrm{m}^2$), featuring high time resolution ($\Delta t \leq 2\,\mathrm{ns}$) and low ground particle detection energy threshold ($E_{det.} \simeq 20\,\mathrm{MeV}$). Using the high resolution arrival time measurements and the multiple-station information, it is possible to reconstruct the direction and the geometry of atmospheric showers originated by photons with $0.1\,\mathrm{TeV} \leq E \leq 200\,\mathrm{TeV}$. This leads to a nearly continuous observation of the sky within a field of view (FoV) of approximately 2 sr and to a high background rejection efficiency, although strongly dependent on the EAS energy. Assuming the observing site to be located at 23° S, the instrument would grant an excellent coverage of the Galactic Plane, with the possibility to monitor a wealth of VHE sources in the Milky Way and beyond (Fig. 1, right panel).

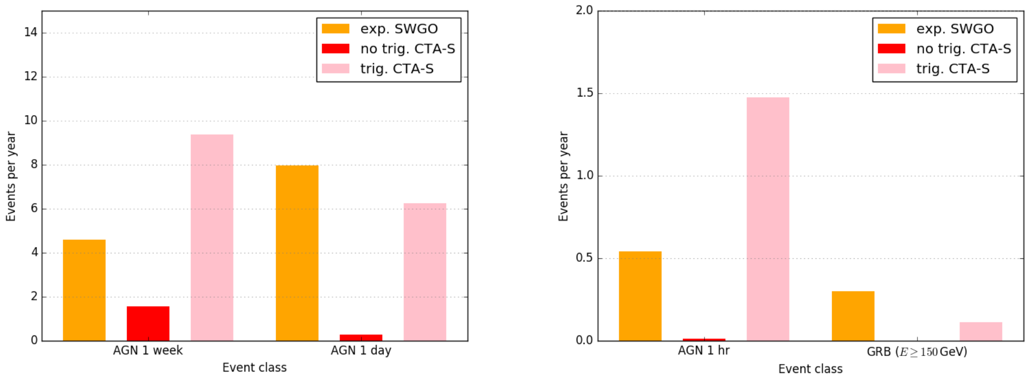

Figure 2: Expected detection rates for AGN flares lasting 1 week and 1 day (left panel), or AGN flares of 1 hour and GRBs (right panel) using data from SWGO (orange bars), CTA South without trigger (red bars) and CTA South alerted by a positional trigger (pink bars).

In particular, the most important extragalactic sources of γ rays are AGNs, mainly blazars, and GRBs. The VHE emission is unpredictable and can last from few hours (in the case of GRBs) up to some days or months (in that of AGNs). Due to this limited time span, the chance to detect the transient in an early stage is a critical requirement to trigger instruments that need to be properly pointed.

On the basis of the monitoring carried out in the *Fermi*-LAT All Sky Variability Analysis (FAVA, [3]), it appears well established that blazars show a spectral hardening, when entering a flaring state. By comparing the distribution of sources in the right panel of Fig. 1 and their extrapolated fluxes with the sensitivities scaled to the available amounts of observing time (in the assumption that short flares are more numerous than long ones), we can estimate the chances of detection of these transients through a monitoring instrument, like SWGO, or by means of a specifically triggered CTA observation, as shown in Fig. 2. We can follow a similar approach for GRBs, although the unpredictable distribution of the events and the still scarce statistics of VHE detections make this analysis subject to a larger uncertainty. It has been proven that GRBs can produce VHE photons, but the mechanisms are still unclear. Since in 10 years *Fermi*-LAT has detected 169 GRBs above 100 MeV, while only a dozen emit at $E \geq 10\,\mathrm{GeV}$ [5], after accounting for the LAT effectvive area and assuming that the number of events producing photons above a minimum energy E_{low} obeys a power-law $N(E > E_{low}) \propto N_0(E/E_0)^{-k}$, with $k = 1.50$, we can expect that roughly 2-3 events per year may radiate above 150 GeV. Given that their observation with an IACT requires the trigger to be promptly reported and to occur in favourable observing conditions (clear Moon-less night), the chances of detection for such events would be greatly enhanced by a facility like SWGO, leading to expected detection rates up to 1 event every 1-2 years.

4. Summary

With its high duty cycle and wide FoV, SWGO will be able to monitor vast areas of the sky, mapping VHE emission from the Galaxy and increasing significantly the probability to detect and track transients of different nature. Most of the Physics that is associated with VHE emission, however, require the instrument to be sensitive to the sub-TeV domain, where emission from GRBs has been recently confirmed. This poses several challenges that can only be addressed by a highly optimized design of the instrument and its data processing systems.

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