Rare Events searches with Cherenkov Telescopes

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Abstract. Ground-based Imaging Cherenkov Telescope Arrays observe the Cherenkov radiation emitted in extended atmospheric showers generated by cosmic gamma rays in the TeV regime. The rate of these events is normally overwhelmed by 2–3 orders of magnitude more abundant cosmic rays induced showers. A large fraction of these "background" events is vetoed at the on-line trigger level, but a substantial fraction still goes through data acquisition system and is saved for the off-line reconstruction. What kind of information those events carry, normally rejected in the analysis? Is there the possibility that an exotic signature is hidden in those data? In the contribution, some science cases, and the problems related to the event reconstruction for the current and future generation of these telescopes will be discussed.

1 Introduction

Gamma-ray Astronomy is the branch of science that observes the cosmic radiation beyond the keV. Below some tens of GeV, such observation is done mostly through pair-production instruments (e.g. the Fermi-LAT instrument[1]) or Compton-scattering instruments, mounted on satellites. Above few tens of GeV and below several tens of TeV, observations are mostly done with Imaging Atmospheric Cherenkov Telescope Arrays (IACTA) that observe indirectly gamma rays through the Cherenkov light produced by atmospheric particle shower initiated in the high Earth atmosphere by cosmic gamma rays. Despite this technique has only 3 decades now, it has already reached a mature stage [1, 2], with about 150 sources detected, and a world-wide installation soon to be deployed, under the name of CTA (Cherenkov Telescope Array [3]).

There are currently three major installations of IACTA: H.E.S.S., MAGIC and VERITAS[2] that are under operations for about a decade now. These instruments perform stereoscopic observations of the same event with multiple telescopes: the Cherenkov radiation from the atmospheric shower, generates, on the cameras of the telescopes, an ellipse-like shape, whose image treatment allow inferring the direction and energy of the corresponding primary cosmic gamma ray. To image an event, IACTA cameras are constituted by more than a thousand pixel each (the individual pixel is typically a photomultiplier tube of typically 0.1 deg aperture). In such instruments, there are several layers of triggers and selection of events, some acting online, some offline. The first levels need to exclude the noise events caused by the Light of the Night Sky, due to starlight, zodiacal light and airglow. This is

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done online. A rate of about 200 Hz of events passing this selection is typically stored on disk[3]. However, most of these events do not correspond to gamma rays, but instead are comprised of atmospheric shower events initiated by cosmic rays (mostly protons, with traces of heavier nuclei). The hadronic background at this stage outnumbers the gamma-ray events by more than a factor of hundred. Later on during the data reconstruction, these hadronic events are rejected by further image cleaning and selection. However, not all background can be rejected, specially at the lowest energies, where the images are more dim.

In this contribution, we briefly discuss the possibility that some of the background events can have actually a different origin, in some cases even hiding signatures of exotic and fundamental physics. We argue that one can develop special reconstruction and analysis treatment to extract these events. We are motivated to discuss this issue by gathering together different phenomena, for two reasons: from one side, the search of hidden signals in the background data of IACTA share similarities (special image cleaning, special data selection, whole data sample access, blind signal searches), and from the other side, it could be timely to consider fast selection filter for the CTA instrument. The reason is that, while current IACTA can manage to save data on disk because the space occupation is limited (about 1 TB of data/day for, e.g., MAGIC), for CTA the situation will be more dramatic, with expected 100 TB data/day or even more. In order to reduce the occupancy, CTA is planning to preselect and delete some information on the events. If this will not be done efficiently, CTA will risk to throw away possible extremely interesting events in its data haystack.

A search for such needles in the haystack would require several dedicated steps in the reconstruction and analysis:

1. A dedicated Monte Carlo. All events of IACTA are determined by comparing the image in the multipixel camera with the corresponding Monte Carlo simulation. For gamma rays and hadrons, this is done using the Corsika code. For peculiar events, one should additionally develop a code for the interaction of the cosmic particle with the atmosphere. It is clear that in some cases, when an exotic particle is under scrutiny, such Monte Carlo will be not only complex to develop, but will rely on theoretical ansatz;

2. A dedicated image cleaning. The standard image cleaning (although different techniques were proposed in the past) relies on the extrapolation of the event image by "cleaning out" those pixels whose signal is very likely caused by the Light of the Night Sky. The procedure is optimized for ellipse-like shapes (like those coming from gamma rays) through the so-called Hillas parameterization [4]. Some rare events could have instead very peculiar images (small bright spots, multiple images, etc, – see below). A dedicated procedure should thus be prepared;

3. A dedicated parameterization of the event and extraction of primary information (direction, energy);

4. A dedicated high-level analysis.

It is clear that the finding of one event will very likely not be sufficient to infer a detection. All rare events should happen with sufficient statistics to be visible above an unresolvable background.

2 Rare Events in the Background sample

The first class of rare phenomena that will be discussed is composed of events that have passed the first on-telescope trigger criteria, have been rejected by the standard analysis, and are stored on the disks. Of these events, some could have a classic nature, some could belong to more exotic explanations.

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[3]For the ten years of operation of MAGIC, considering an average datataking of 5 h per night, this rate corresponds to about 12 GEvents saved on disk

2.1 Heavy Nuclei

In 2007, H.E.S.S. reported the measurement of the spectrum of cosmic iron nuclei from 13 TeV to 200 TeV [5] with five spectral points. Their data nicely overlap previous measurements taken with balloon experiments. Events from iron nuclei are two orders of magnitude less frequent than proton-induced shower, and for this reasons are harder to detect. However, the signatures in IACTA from heavy-nuclei-initiated showers have different features than those of proton or gamma rays. The nucleus is charged and proceeding with relativistic speed. Therefore, a small but intense burst of Cherenkov radiation is *directly* produced by the nucleus itself in the high atmosphere. As soon as it travels down, the nucleus has interactions with the denser atmospheres initiating an hadronic shower, rather similar to that of the protons. Therefore, in the camera, an iron event is composed of two spots: a bright spot toward the center of the camera (high in the atmosphere) arriving earlier, followed later in time by the classical ellipsoidal shape of the atmospheric showers and aligned with the main shower axis. The analysis is not straightforward, but proven possible. Besides H.E.S.S., no other IACTA has tested this method.

One could ask whether other heavy ions can be seen in the cosmic ray spectrum, whose abundances per element are measured at lower energies with balloons (see, e.g. [6]). Particles like CNO or Si are not only rarer because of lower fluxes, but also would provide less photon yield (that goes as Z^2). However, specially with future generation of telescopes like CTA, with better sensitivity and larger energy range, such searches will be possible.

2.2 Tau-Neutrino searches

Several classes of astronomical targets including massive black holes at the center of active galaxies or gamma-ray bursts, are expected to produce significant radiation of neutrinos. Irrespective of the family of neutrino at the production place, for extragalactic distances, the mixing foresees that the neutrino families at the earth should arrive in equal fraction, and thus that cosmic tau-neutrinos should be observable at Earth. These have not yet been discovered in cosmic neutrino detectors, however, they may be observable with IACTA through a phenomenon called Earth-skimming taus [7, 8]. Shortly, if a tau-neutrino crosses the right amount of ground (the Earth crust, or water), of the order of few tens of km, tau-leptons can be generated through deep inelastic scattering processes like $\nu_\tau + N \to W^+ \to X + \tau^-$ If the tau-lepton later on emerges from the medium, it creates an atmospheric shower. Suppose now that a telescope is located at the right distance from the exit point of the tau-lepton, it could detect the emerging atmospheric shower. From such directions, a shower could be not explained by other mechanisms. Searches like this were performed by MAGIC looking at the right direction toward the Canarian sea, reporting for now only results on the feasibility of the technique, but still no detection [9]. The expectation on the flux are extremely low: the diffuse neutrino flux can provide few events per decade. However, in case of strong or flaring astrophysical sources, the neutrino flux could be enhanced, thus providing still dim, but detectable signals. When one then compares the sensitivity of e.g. CTA compared to other instruments like Auger or IceCube, one can see that for "low-energy" PeV neutrinos, the CTA sensitivity could be larger than the others, thus providing sufficient ground for a careful search [10]. MAGIC developed the selection criteria for these events, showing that tau-neutrino induced events are in principle observable in the data.

2.3 Magnetic Monopoles

Magnetic monopoles were predicted back in 1930 by Dirac to explain the electric quantization. Later on during the century, it was found that magnetic monopoles appear naturally in Grand Unification

models [11, 12]. In particular, some theories predict that they are formed during the QCD phase transition in the early Universe, and, being stable, they could still be present in the actual Universe. When a magnetic monopole crosses the Earth atmosphere, it will produce a huge number of Cherenkov photons, about 4700 times than those produced by a gamma ray [13]. In addition, the Cherenkov photons from magnetic monopoles will be produced throughout the full length of the atmosphere, and not from a limited path as when originated by atmospheric showers. This event would be observable by an IACTA as extremely bright spots or short lines, and not like ellipse-like shapes. The search for magnetic monopoles events has already been accomplished by H.E.S.S. [14] and the expectation for CTA were discussed in [15]. However, other instruments like Auger or IceCube seems to have higher sensitivity [16, 17]. One should also mention that IACTA would be sensitive only to ultrarelativistic magnetic monopoles, while other instruments have wider capabilities [18].

2.4 Antiquark Matter

In order to explain the matter-antimatter density inequality in the present Universe, some theories predict that during baryogenesis, the antimatter content was confined into very high dense states of quark plasma by the formation and subsequent collapse of domain walls in the existing quark-gluon plasma [19, 20]. Such aggregation would be composed of a huge number of antiquarks (or quarks), in the order of $10^{25} - 10^{35}$, and have survived until present times in the intergalactic medium. These aggregation are called "quark nuggets" and share similarities with the strangelets [21]. They can be considered as viable dark matter candidate, at least comprising a fraction of the total density. The quark nuggets would be dressed with leptons to be globally neutral. In several works of K. Lawson, and specially [22], the direct and indirect detection techniques for quark nuggets are described. In particular, the quark nuggets are expected to emit charged particles and high-energy radiation when crossing the Earth atmosphere, thus initiating an extended atmospheric shower. The main difference with respect to standard cosmic showers would stem from the fact that the nugget will not decay in the atmosphere, and that its velocity is much lower than that of cosmic rays, typically of the order of the galactic velocities. The passage will then be seen as a "stripe" on the camera of the telescope, developing slowly from one side of the camera to the other, considering the nugget velocity, and increasing in brightness toward the ground, where the nuggets interactions with the denser atmosphere would increase.

No dedicated search for these exotic states has been performed with IACTs so far. However, the search would share similarities with the case of magnetic monopoles, as discussed in [18].

3 Rare Events in the Field of View

Not only one can have peculiar events in the background data haystack, with specific signatures in duration, time evolution, shape, etc., as described in the previous section, but additional rare events could occur serendipitously within the field of view, passing undetected, unless a specific analysis is developed. It is clear that a steady source or very brilliant flaring source in the field of view is recognized through the standard analysis. Here we are discussing examples of very brief events, lasting seconds or less, that would not appear when integrating over larger time windows.

3.1 Primordial Black Hole Evaporation

There are several mechanisms that allow the creation of primordial black holes (PBHs) in the Early Universe, besides those of astrophysical origin. Depending on the Universe average density at a given

time after the Big Bang, these PBHs could have a specific mass. However, the range of possible masses is large: from the Planck mass to 10^5 M$_\odot$ [23]. As the time passes, a PBH increase its temperature and radiate energy, toward the final phase when Hawking radiation is emitted, and the BH evaporates. The life expectancy of a BH can be computed and depends solely on the BH mass. As the evaporation time approaches, the BH radiates more on more. This means that, at present times, we could be seeing the evaporation of all the PBHs of a *given* mass. A description of the lightcurve and gamma-ray spectrum of emission from an exploding PBH can be found in [24]. Shortly, the gamma-ray emission would be stable for most of the time, while an exponential increase in the last minutes to seconds to the evaporation is predicted.

PBH evaporation could be therefore appear as short bursts of emission randomly in the FOV of an IACTA regular observation. Bright and steady sources in the FOV are in principle easily seen in these data. However, in this case the emission would be more subtle to find and its observation would require a dedicated analysis: the emission could be dim, and specially short in time, and therefore washed out by integration over large duration. The PBH search should be performed over the whole data sample of an IACTA. This requires some non-standard data handling. The Whipple gamma-ray telescope pioneered this search [25], however, much better sensitivity can be expected with CTA.

3.2 Fast Radio Bursts

Fast Radio Bursts are very short $(1 - 10$ ms) bursts of radiation discovered in archival radio data few years ago [26]. Besides their short duration, the main characteristics is that the radio emission shows a large wavelength dispersion, which hints to extragalactic origin ($z \sim 1$). They could be originated out of neutron stars or magnetars formation or merger events [27]. These peculiar extreme events recently raised attention in the astrophysics community, however, their true nature is still to be clarified. When computing the intensity, it is possible that these events are accompanied by the emission of gamma-ray radiation at TeV energies. Very similarly to the PBH case discussed above, they would therefore appear as very short and intense spots in IACTA skymaps. The light curve should be different from that of PBH, so they could be discriminated. No result is published yet from IACTA in search of these targets.

4 Discussion and Conclusions

In this contribution, we have briefly discussed few possibilities to search for rare events among the data gathered by ground-based gamma-ray detectors of the IACTA class. These rare events share some features: they would probably go undetected by standard reconstruction and analysis techniques, thus they would require dedicated simulations, data selection, image treatments and so on. We grouped these events into two classes: events that would be mostly tagged as background in the IACTA standard reconstruction, and events that would appear serendipitously in the field of view of the instrument, and could go unnoticed because of short duration or faintness.

Past and current instruments have performed searches and published results around some of these topics, some instead are not investigated yet. These projects share complexity in terms of data handling and often suffer from incomplete theoretical mapping. However, in most cases, these investigations would not require allocation of instrumental time. They would mostly imply a careful treatment the large dataset of archival data gathered by the current instruments, which is now comprised of about a decade of data.

Because the current instruments generate a large but not huge amount of data per night, basically all data that triggered the telescopes are safely stored on disks, including a large fraction of background

(cosmic ray) data which is normally partly unused in the advanced steps of the analysis. However, the future large installation of CTA will produce a very large amount of data per night, which would demand an effort to reduce consistently the full information, e.g. by excluding some pixels from the image event, or reducing the amount of background-tagged events stored on disk. For gamma-ray searches, this is an optimal solution, but for the search of rare events proposed here, this could be a killer factor. It is therefore envisaged to develop robust and fast routines that could tag interesting not-standard events and save them for further analysis. It is clear that such routines should be developed well on time before CTA starts operation, which is expected soon after 2020.

Acknowledgements

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