Archival search for Young Stellar Objects in the VERITAS data

DESY Summer Student Programme, 2012

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31th of August 2012

Abstract

The study of young stellar objects (YSOs) at very high energies (VHE) could be the key for the several open questions on star formation. Thanks to the RMS server we are able to find the positions of the YSOs in all the previous VERITAS observations. After analysing our massive YSOs choice, we established the upper limit fluxes for each one and we found a promising candidate which points to a possible detection in the future with further observations.

Contents

1 Introduction

Young stellar objects (YSOs) are stars in the first stages of their life. Generally they are classified in two groups: protostars or pre-main sequence stars (PMS), depending on the existence or not of surrounding matter (gas and dust) falling into the star. YSOs are also associated with physical phenomena like polar jets and bipolar outflows, masers, Herbig-Haro objects or circumstellar disks.

Recently, massive young stellar objects (MYSOs) have been suggested as a possible gamma-ray sources *(Araudo et al. 2007; Romero 2008; Bosch-Ramon et al. 2010).* They have associated bipolar outflows, two gas flows from the poles of the star, interacting with the surrounding medium. There it is possible produce strong shocks where particles can be accelerated up to relativistic energies. Relativistic electrons and protons can then produce gamma-ray emission, allowing us to study them in very high-energy range (VHE) [1].

A common feature of VHE gamma rays sources is that the number of emitted photons decreases rapidly with increasing energy. In addition, the flux from these sources is small; for example, the flux above 1 TeV from the Crab Nebula (considered to be the standard candle in TeV gamma rays) is $\sim 1.5 \times 10^{-7} m^{-2} s^{-1}$. This leads to the requirement of a collection area of order $10^4 m^2$. Such large instruments cannot be launched into space and therefore must reside on the Earth, requiring that the atmosphere becomes an integral part of any detection system [2]. Thus, the reconstruction of VHE gamma rays is carried out in an indirect fashion.

When a high energy gamma ray photon enters the atmosphere it dissipates its energy through the creation of an electron-positron pair. These particles in turn dissipate their energy through the bremsstrahlung (or *braking-radiation*) process in the Coulomb field of the nuclei that comprise the atmosphere. This cycle of pair production and bremsstrahlung continues, leading to the near exponential growth in the number of particles as a function of the depth traversed through the atmosphere accompanied by the corresponding reduction in the average energy per particle. This cascade of particles is called an extensive air shower (EAS) [3]. The charged particles (i.e., electrons and positrons) in the EAS whose velocity is greater than local light velocity produce Cherenkov radiation. The following equation (1) is the Cherenkov condition

$$nv/c = n\beta > 1 \tag{1}$$

where n is the local refractive index in air, which scales with height. The number of Cherenkov photons per unit path length of a particle with charge ze and per unit photon wavelength interval is given by Frank-Tamm formula:

$$\frac{dN}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right) \tag{2}$$

where α is the fine structure constant. It is also important to know that Cherenkov light is emitted along a cone with half opening angle θ, satisfying

$$cos\theta = \frac{1}{\beta n} \tag{3}$$

Due to the fact that index n is a function which depends of height and velocity β, the majority of Cherenkov photons hit the ground in a circumference with radius $\sim 130m$ called *light pool*. In Fig. 1 is represented a schematized plot of this process. For our case, we are looking for Cherenkov photons in ultraviolet (UV) wavelength.

In order to collect the information from Cherenkov radiation we need Imaging Atmospheric Cherenkov Telescopes (IACTs). They use focusing mirrors to image the Cherenkov light emitted by the shower particles onto a camera consisting of individual photo-detectors. Thus, you can reconstruct information of the primary particle, in this case the gamma-ray, like energy or direction (we will talk about this process in the next section). There are currently three operating IACT systems: HESS, MAGIC, and VERITAS, we will analyse data of the latter.

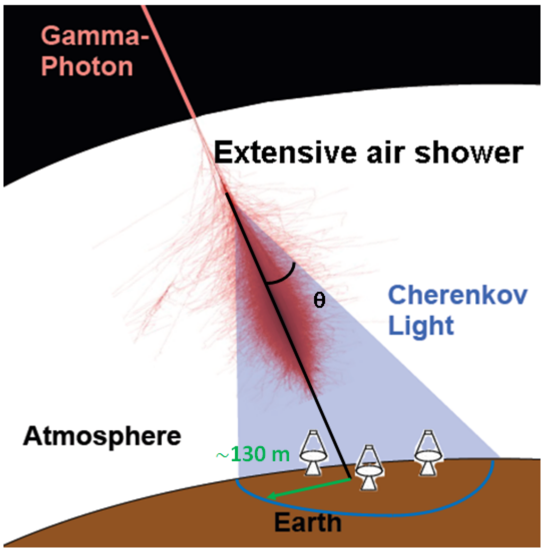

Figure 1: Schematic representation of a gamma-ray coming from the space which enters the atmosphere generating an extensive air shower where charged particles whose velocity is greater than local light velocity produce Cherenkov radiation, being the latter observable with Imaging Atmospheric Cherenkov Telescopes (IACTs). Cherenkov light is emitted along a cone with half opening angle θ and the light pool radius is $\sim 130m$.

Located at the basecamp of the Fred Lawrence Whipple Observatory in southern Arizona (USA), VERITAS (Very Energetic Radiation Imaging Telescope Array System) is a major ground-based observatory with an array of four 12-m diameter Cherenkov Telescopes for gamma-ray astronomy in the very high energy range [1] (See Fig.2)[4].

Each camera comprises 499 photomuliplier tube pixels and light concentrators arranged in a hexagonal pattern with a total field of view (FOV) of 3.5°. The combined instrument has an angular resolution of $< 0.1°$ (68 % containment). In order to eliminate background noise a three-level trigger system is used. The first trigger occurs at the pixel level, requiring the signal to reach a 50 mV threshold set by a constant fraction discriminator (CFD). The second requires at least three adjacent pixel passing the CFD trigger to form an image. A third, array-level trigger requieres simultaneous Cherenkov images in at least two telescopes, within a 50 ns time window, which then causes a readout of the 500 MSample/s FADC (see *Data Analysis* section) data acquisition system for each pixel.

This project is motived by the fact that the study of YSOs in VHE could be an essential step toward deciphering the origins of stars (there are several open questions on star formation) and planets, to understand particle acceleration processes in the complex environment of massive molecular clouds, to unravel the formation mechanism of astrophysical jets in TeV.

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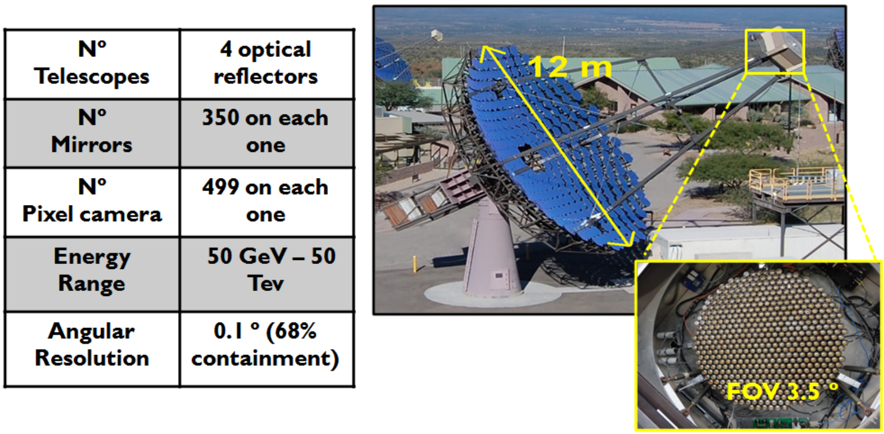
[1] Very High Energy ranges between 50 GeV and 50 TeV



Nº Telescopes	4 optical reflectors
Nº Mirrors	350 on each one
Nº Pixel camera	499 on each one
Energy Range	50 GeV – 50 Tev
Angular Resolution	0.1 ° (68% containment)

Figure 2: On the left side a VERITAS technical snapshot. On the right side, one of the four Cherenkov telescopes and the camera, with a Field of View (FOV) of 3.5 degrees.

2 RMS Server

Since the aim is to detect YSOs in very high energy range, the question is where are they and how can we be sure that they are really YSOs?.

The Red MSX Source (RMS) survey [2] is a multi-wavelength programme of follow-up observations designed to distinguish between genuine massive young stellar objects (MYSOs) and other embedded or dusty objects, such as ultra compact (UC) HII regions, evolved stars and planetary nebulae (PNe). RMSX has identified nearly 700 MYSOs candidates. Using this database we know the position, plus other information, on these MYSOs [5].

Fig.3 shows time required to detect a source at 5σ as a function of source strength in Crab Units [6]. We assume YSOs will not have flux higher than a few % otherwise might have been seen. The positions of the YSOs were compared to all the previous VERITAS observations (see Fig.4) and we choose 118 sources with 10 hours minimum.

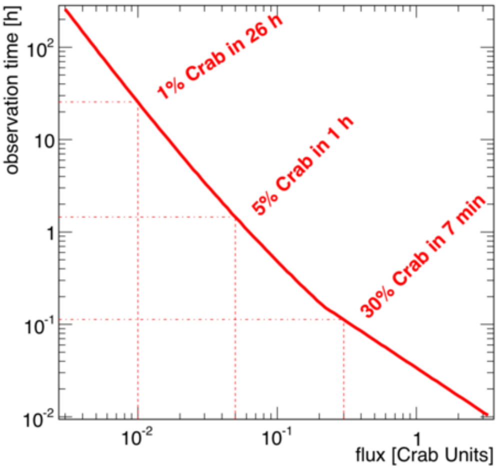


Figure 3: Relation between flux, in Crab units, and observation time in hours to be able to detect 5σ objects (red line).

3 Data Analysis

Before starting to analyse the data, some calculations and inspections are required in order to reduce data and to remove bad observations. This section will describe the analysis chain.

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[2] The survey was conceived at Leeds to search the entire Galaxy for massive young stellar objects, MYSOs ($L > 10^4 L_\odot$), systematically.

As every photomultiplier tube (PMT) is different, we need to do a set of calibrations to have an uniform response across the camera. In order to do it, light pulses [3] are fired at the cameras, hitting all the PMTs at the same time and with similar intensity. Usually a 5 minute calibration run, where the diode flasher is at 300 Hz, is taken each night to accommodate for any changes in the PMTs over time [7]. This technique is called *flatfielding*. The first step is then obtaining the flatfield of each night to calibrate our observations.

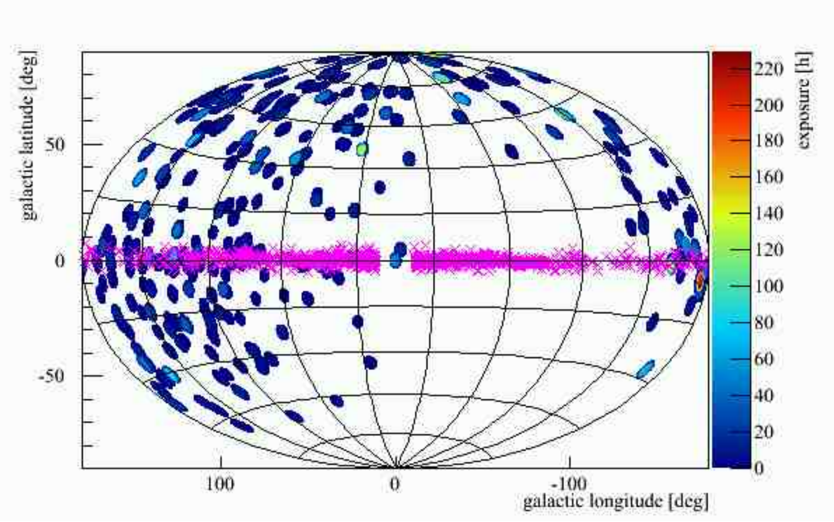

Figure 4: This picture shows the sky in galactic coordinates (galactic latitude versus galactic longitude in degrees). The violet crosses are the positions of the MYSOs according to RMS database. The circles are the VERITAS observations where the colour indicates the exposure time.

The fast Analog-to-Digital Converter (FADC) records the events by storing the charge measured in the PMTs of all telescopes. These traces are related to the amplitude of the light in tube in digital counts (d.c.). After the flatfield correction, for each observation, which has a RUN number asociated, we have to integrate to obtain the total charge in each pixel. This integration is done over a selected time window, 12 samples of 2 ns in our case.

The next step is to reconstruct the geometry of the primary particle (see Fig.5).

- The shower images are fit to a 2D Gaussian to find the length and the width.
- The source position is reconstructed at the intersection of the major axes in camera coordinates.
- The core location of the shower, where it hits the ground, is reconstructed using the major axis of each image, working in ground coordinates.
- In order to differentiate cosmic-ray images from the gamma-ray images we use Monte Carlo simulations. It is very important to do it well since there are 1000 times

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[3] To have an uniform response across the camera, a nitrogen laser with a dye module which fluoresces at 330 nm is used. Later the laser was replaced by a blue frequency LED.

more cosmic-rays than gamma-rays. Fortunately, background/proton events are more asymetric and we can take advantage of this fact on the cuts that are placed on the width and length of the images.

- The shower energy is linked to the image size and the impact parameter, so that Monte Carlo simulations are needed again. These simulations are stored in lookup tables which we use to obtain the energy.

At this point, in order to extract a potential gamma-ray signal, an accurate background estimation has to be performed. It is estimated for each bin of the skymap by using an annulus (ring) region around the bin (see Fig.6).

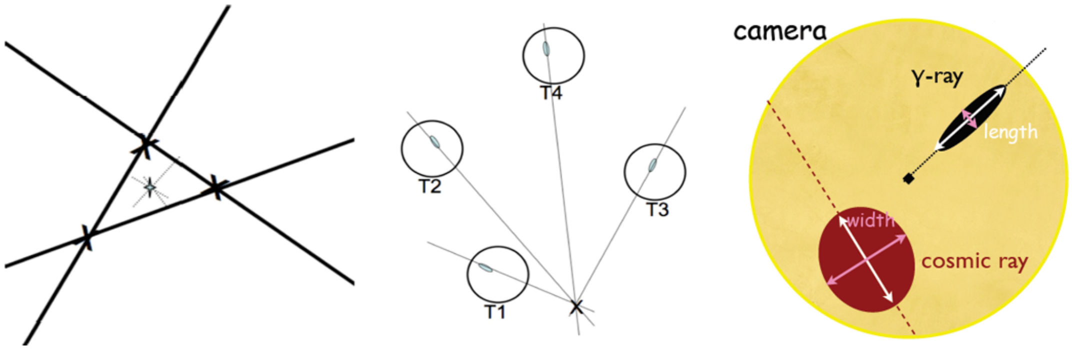

Figure 5: 1- The source (star) position is reconstructed by minimizing the perpendicular distances (dotted lines) from the major axes (solid lines). 2- Example of how the core location is determined in the plane perpendicular to the telescope pointing direction (in spatial coordinates). 3- Representation of a cosmic-ray image and a gamma-ray image in the telescope camera. Length or width parameters can be used to reject cosmic-rays from our observations.

In order to avoid the contamination, it is important that any gamma-ray source or bright stars (magnitude < 6) in the field of view be excluded from the background estimation region. The gamma-ray source at the center of the field of view is also excluded from the background estimation.

Once it has been estimated, the significance of a gamma-ray signal can be calculated to create significance sky maps.

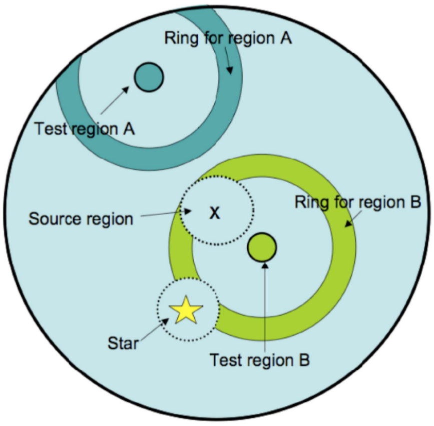

Figure 6: Rings used to estimate the background for two test regions. The gamma-ray source at the center of the field of view is excluded from the background estimation, as well as the star region.

4 Results

In the end we successfully analyze 106 objects: 51 are YSOs and the rest HII regions, OH/IR stars, diffuse HII regions or old stars that were identified by the server. In Fig.7 is shown a significance distribution for every object, in the center just for the YSOs and a last one for the other objects. If there is not gamma-ray emission in YSOs we will expect that data could be fit to a Gaussian $N(0, 1)$; nevertheless, you can see a slight tendency to the right that could be a hint but is not enough to conclude something sure.

The brightest infrared young stellar objects, IR YSOs, have more molecular mass available for proton-proton collisions and Bremsstrahlung interactions than those that are faint. It is expected then that the brightest IR YSOs would show the highest gamma-ray luminosity [1]. Since we know the IR flux from RMS database and we have the gamma-flux, the idea is to represent these observables to find the theoretical relation, however there is no correlation between these variables (Fig.8).

We kept going looking for hints in the data. In Fig.7 you can see a YSOs whose significance is 2.8σ, the most significant. We calculated the cumulative significance, i.e., the way that significance changes with time, for our interesting source.

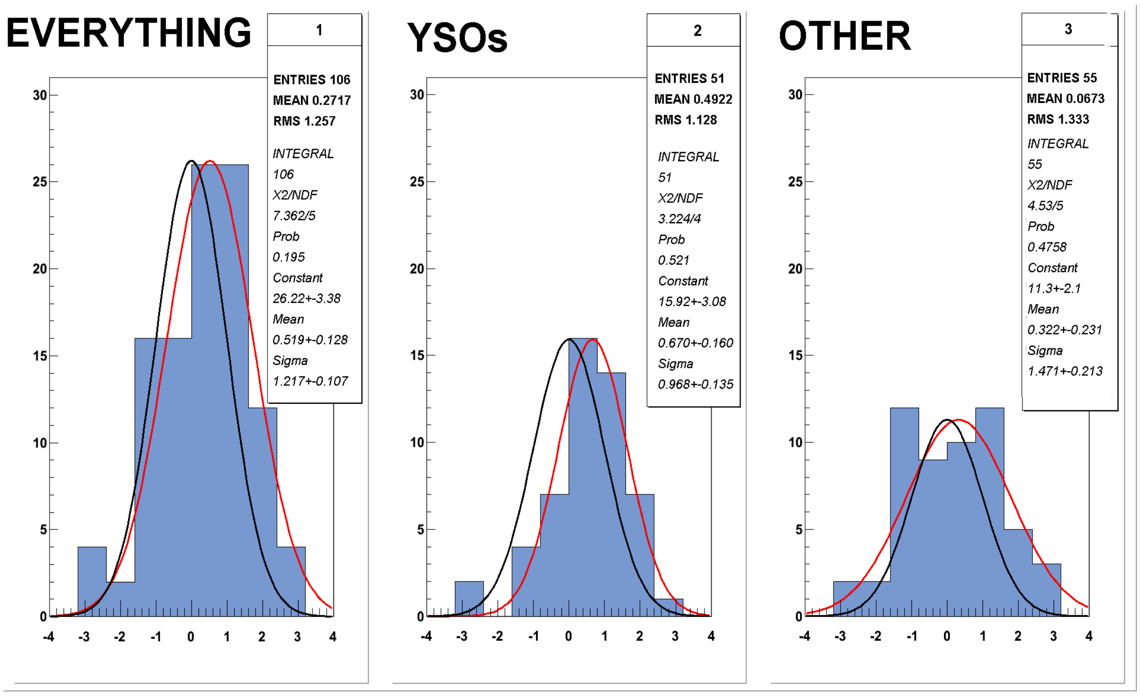

Figure 7: From left to the right: 1- Histogram with our 106 objects, 2- Histogram just with YSOs (there are 51), 3-The rest of objects (HII regions, OH/IR stars, diffuse HII regions or old stars). Every plot has two fits: the black one represent a standard normal distribution, the red one is the fit of the data plotted in the graph in such a way that you can compare how big is the difference between the fit and a $N(0, 1)$ distribution.

We expect a proportional law between them if the YSO has gamma-ray emission

$$\sigma \propto \sqrt{t} \tag{4}$$

Fig.9. shows the cumulative significance of the source and a random patch of sky in order to compare the behaviour of the functions. The former has a increasing slope, which is really interesting for us, while the latter does not present a relation between the represented variables.

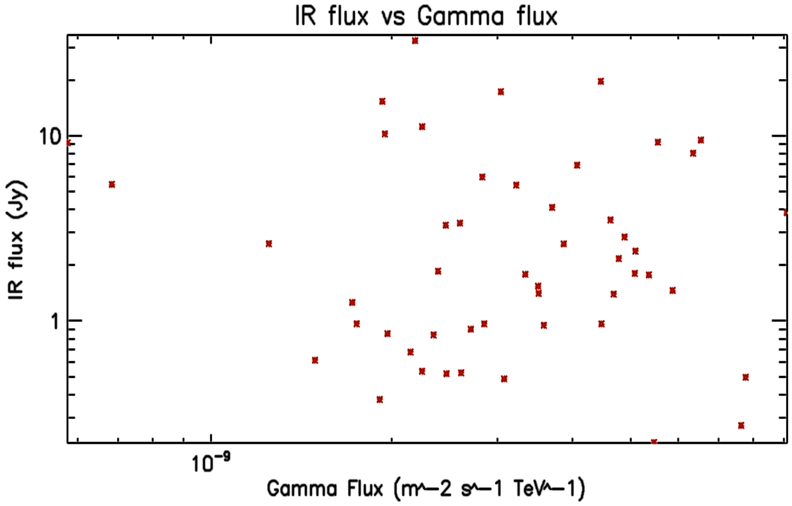

Figure 8: Infrared flux (Jy) from RMS server versus Gamma-ray flux (m^{-2} s^{-1} $TeV^{-}1$) from VERITAS observations. Unfortunately, not relation between these variables can be established in despite of theoretical expectation.

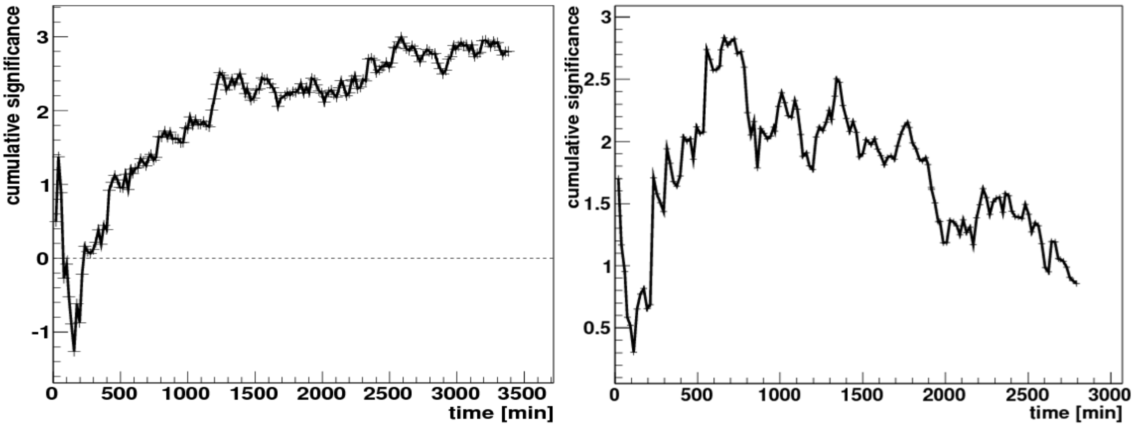

Figure 9: Cumulative significance versus time (in minutes) for YSO and a random sky patch. The increasing significance in the YSO plot can be appreciated while, on the other hand, the random source has an oscillating behaviour.

Since a fit for the cumulative significance is possible (see Fig. 10), we can estimate how long it would take the observation to obtain 5σ. For our YSO we estimated around 165 hours of observations that means an extra 115 hours.

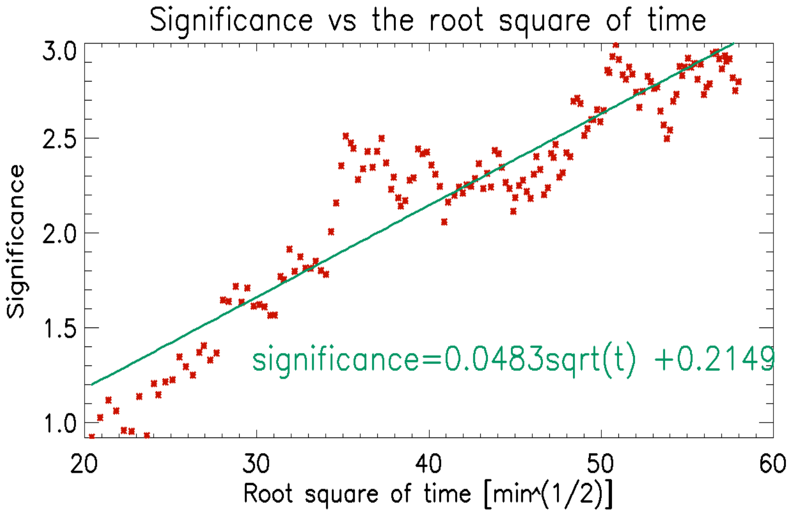

Figure 10: Significance versus the root square of time (in minutes). A linear fit was made in order to estimate how long is going to take the observation to obtain 5σ.

Other interesting information is the upper limit flux, e.g., for people working in protostellar modelling to set a maximum value in their simulations. It is the calculated flux plus 3 sigma in order to establish with a 99.73 percent certainty that the sources can not emit energy above this value. In Fig. 11 is shown a histogram for the 106 studied objects.

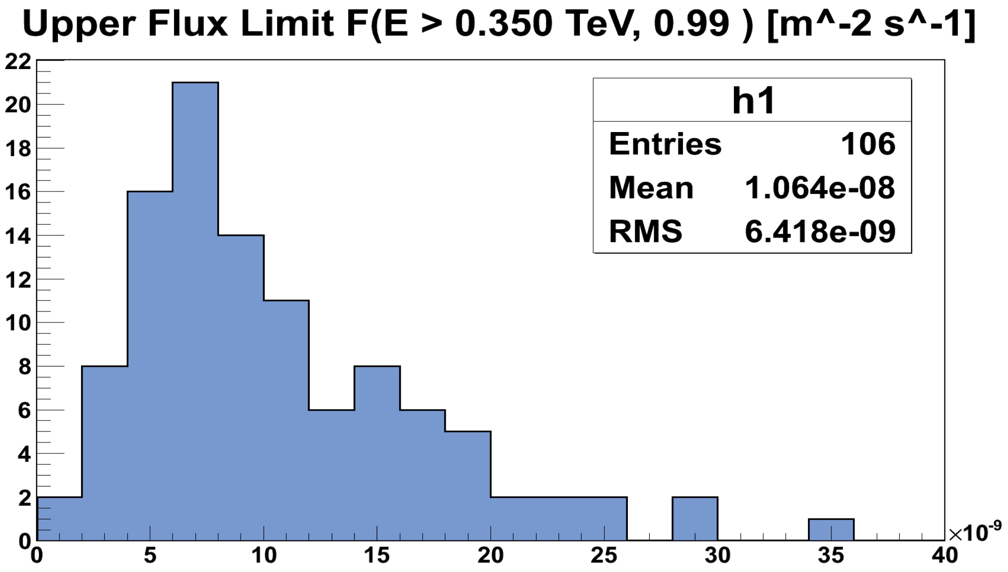

Figure 11: Histogram with the upper limit flux in $m^{-2}s^{-1}$ calculated with 3σ for the 106 studied objects.

5 Conclusions

The information of the upper limit fluxes for every MYOs will be useful for people working in protostellar modelling to set a maximum value for gamma-ray emission in their simulations. The process to obtain this data has been automated, so that it is possible calculate the upper limit flux for any YSOs constrained in VERITAS observations.

The increasing significance on strongest YSO source is really interesting. To check the significance value, we contacted with people who work in VERITAS group as well. The investigator in charge to do the verification obtained a 3 significance for that source using independent chain which is encouraging. However, to get a 5σ result we need an extra 115 hours, i.e., the 11.5 percent of the available time that VERITAS has in a year. Since it is not easily viable, it maybe possible, e.g., to get an extra 10 hours in order to confirm the significance behaviour with time. Depending of the new results, we will consider the best options to do.

The future generation of Cherenkov telescopes will permit to obtain better results for lower observation times. It is the case of Cherenkov Telescope Array (CTA) that will consist of several tens of Cherenkov telescopes, to be compared with H.E.S.S. MAGIC or VERITAS arrays, which use at most four telescopes. Such an array will allow the detection of gamma-ray induced cascades over a larger area on the ground, increasing the number of detected gamma rays, and at the same time providing a much larger number of Cherenkov images of each cascade. This will result in both improved angular resolution and better suppression of the CR background events, and finnally in a 10 times gain in sensitivity of the telescopes [8].

Acknowledgements

I would like to express my gratitude to my supervisor, Gareth Hughes, for his constant help and patience to understand my spanish version of english language. Thanks for *grep* and gawk!. I would also like to mention my group leader, Gernot Maier, whom cared about me one month before starting the program.

I also wish to thank all people who enjoyed some of my crazy plans I have made during the summer to visit cities in Germany with me, specially to Anusorn Lueangaramwong, my room and simulations mate; Aleksandra Słapik, Aleksander Hulist and Willian Matioli.

Furthermore, I am thankful for being chosen in this programme. It was a really good opportunity to apply my astrophysics knowledge and my experience to achieve the objectives of the program, to develop new skills, to learn about teraelectronvolt astronomy and, of course, to improve my english.

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