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Short GAmma Ray Front Air Cherenkov Experiment

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Abstract. Atmospheric Cherenkov Imaging Telescopes can be used to search for GeV γ-ray bursts with a very high sensitivity in the mostly unexplored time scale from $100ns$ to $10\mu s$. In this paper we review the motivations for this search and present the techniques being developed for the SGAR-FACE experiment which will be implemented on the Whipple telescope.

1 Introduction

Gamma-ray bursts observed with space detectors span a wide range of durations which, up to now, is only limited on the shortest side by the detector's integration time to $\sim 1ms$. Among the detected bursts, millisecond and sub-millisecond variability is common (Walker & Schaefer 2000). But space based detectors do not have trigger sensitivity for shorter time scales as their effective collection area would not allow for much faster sampling of signals with usual amplitudes.

Ten years ago, imaging atmospheric Cherenkov became successful in probing the few 100GeV γ-ray astronomical window (Weekes 1989). Experimental development of ground based detectors are currently aiming at lowering the energy threshold below 100GeV (Weekes 1999, Hofmann 1997, Barrio 1998). Nevertheless a 10 meters telescope like the Whipple Gamma Ray Telescope collects about one Cherenkov photon per GeV of the primary γ-ray and sensitivity to individual few 100MeV γ-rays will remain the realm of space detectors.

When a Gamma Ray Burst occurs, a large number of γ-rays interact with the atmosphere at $\sim 20km$ altitude. Each of them produces Cherenkov light which is spread over an area $\sim 500m$ in radius when arriving on the ground. The Cherenkov light from all the showers gives a detectable glow extending over $\sim 2^o$ centered on the direction of the burst. The diffuse night sky background (our sensitivity limitation) of $\sim 940\gamma e \cdot ns^{-1} \cdot m^{-2} \cdot sr^{-1}$ collected over such a solid angle during $\sim 10\mu s$ compares quite well with the Cherenkov

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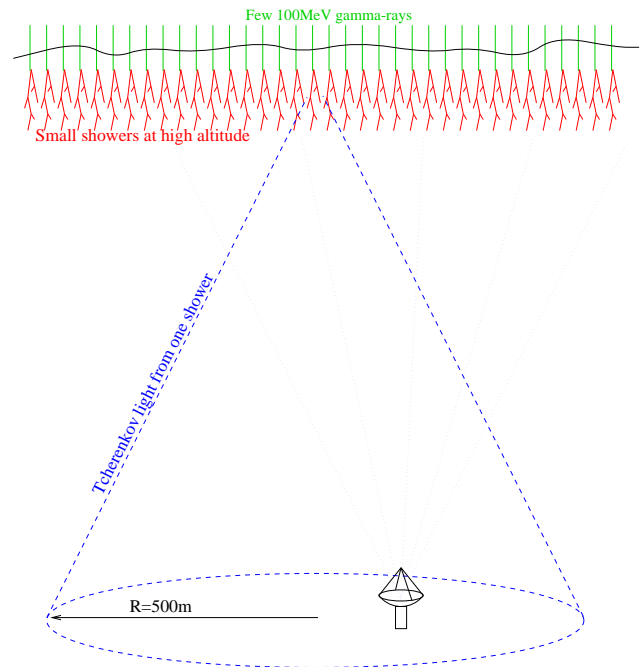
Fig. 1. The Cherenkov light produced by the many tiny electromagnetic showers at high altitude cumulates in a detectable glow. The large radial extension of the visible part is due to the important multiple scattering of the low energy electrons.

light we would receive from a few $100MeV\,\gamma$-ray burst with a fluence of $10\gamma\text{-}ray \cdot m^{-2}$. This also corresponds to the fluence sensitivity that can be achieved with space based detectors with collection areas of $\sim 1m^2$ since 10 photons events is not far from being a minimum required to define a burst. For shorter time scales the sensitivity of Cherenkov detectors improves thanks to the reduction in noise contamination according to the inversed square root of the burst duration and, for 100ns bursts of 1GeV γ-rays, the fluence sensitivity that could be achieved is $\sim 0.1\gamma - ray \cdot m^{-2}$.

In this paper, after describing the Short GAmma Ray Front
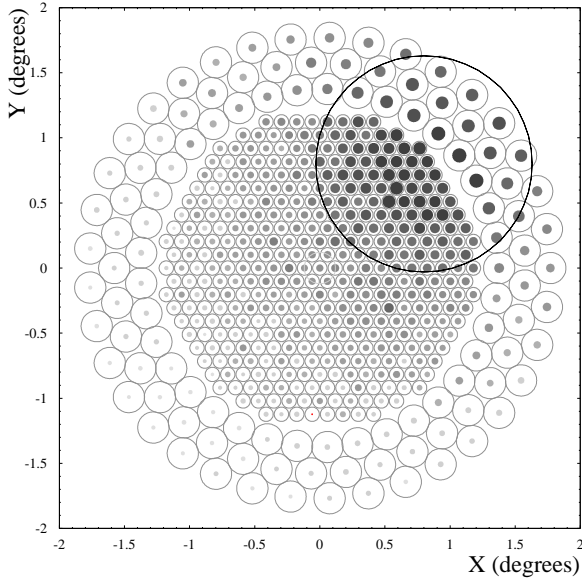
Fig. 2. The images that multi-particle front initiated electromagnetic showers should produce are symmetric with a characteristic radial profile.

Air Cherenkov Experiment (SGARFACE) along with a more precise estimation of the sensitivity it should achieve, we will review the origins and properties of the most likely source of such short γ-ray bursts, if they exist: primordial black-holes.

2 Short GAmma Ray Front Air Cherenkov Experiment

The general idea of the detection technique (Krennrich 2000) has been already outlined in the introduction and in figure 1. For the SGARFACE experiment we are planning on using the Whipple telescope as the Cherenkov signal collector. The signal coming from the photomultipliers will be duplicated before they reach the standard electronic used for TeV observation in such a way that burst observations will not interfere with the usual TeV astronomy data taking. Since the expected images (See Figure 2) induced by a multi-particle initiated shower are quite extended ($\sim 2^o$) in comparison to the whipple camera pixelation (0.13^o), signals used by the SGARFACE experiment will be summed per cluster of seven neighbor pixels bringing the number of channels from 379 down to 55. In the same operation, the band-width is reduced allowing for a 50MHz digitization of the signals with no information loss. According to simulations, an infinitely short burst produces a 50ns atmospheric Cherenkov flash and a 50MHz sampling is sufficient to discriminate these events against the frequent high energy cosmic ray shower Cherenkov flashes which last less than 30ns.

These signals are sent to our Trigger I modules (Figure 3) which digitize them and apply a digital multi-time-scale discrimination as described in the accompanying paper (LeBohec 2001). The discriminator signals are sent to our Trig-
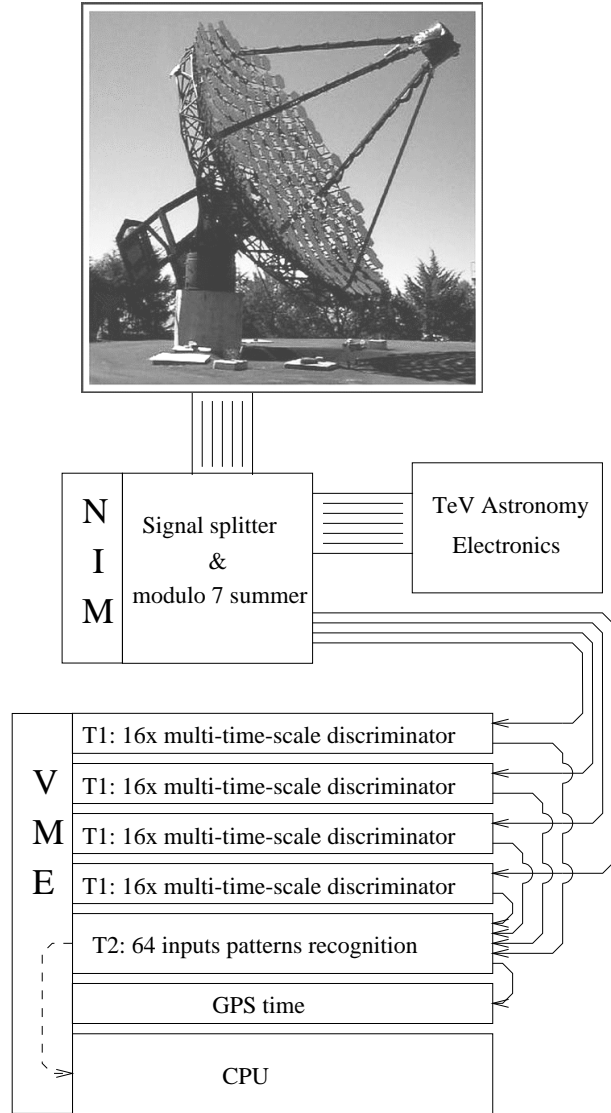
Fig. 3. General scheme of the SGARFACE experiment.

ger II module, a coincidence unit which allows to apply a connectivity criteria in order to further reduce the accidental rates.

The timing and imaging analysis allow us to remove the dominant $100ns-10\mu s$ background due to atmospheric scintillation produced by ultra-high-energy cosmic-ray showers. For this we can use the fact that the features of the multi-particle front initiated shower images are quite unique. Both the light distribution and the time structure of the image centered on the direction of the burst should be symmetric. There is no phenomena known to us that could produce fake signals. In case some good candidates were obtained with the Whipple telescope the final verification would be to reproduce the experiment using at least two telescopes of VERITAS. If the telescopes are aimed at the same direction, a short γ-ray burst should look the same in both telescopes with no parallactic displacement between each other.
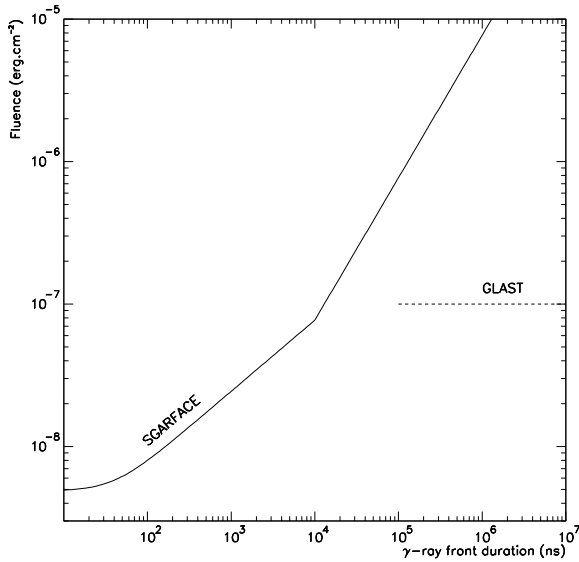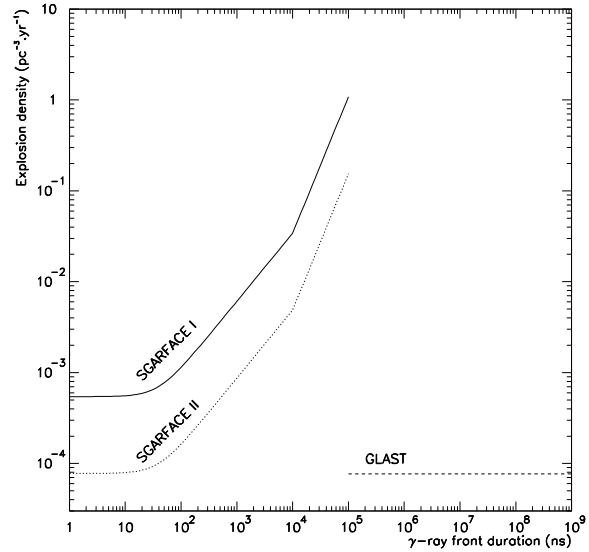
Fig. 4. The fluence sensitivity as a function of the burst duration as it should be achieved by SGARFACE is compared to the burst sensitivity of GLAST for which we assumed a minimum of 10γ-rays required for a burst to be identified.

Fig. 5. Upper limits on the PBH explosion density rate that should be achieved by SGARFACE and GLAST after two years of operation. The dashed line for SGARFACE corresponds to the use of the seven VERITAS telescopes

Detailed simulation of the telescope and signal processing allowed to estimate the sensitivity to be as low as $0.7 \times 10^{-8} ergs \cdot cm^{-2}$ for the shortest bursts (100ns). The sensitivity dependence on the burst duration is shown on Figure 4 and does not depend on the assumed energy spectrum.

3 Primordial black-holes

Primordial black-holes as introduced by Zeldovich in 1966 would result from the collapse of horizon scale density fluctuations in a Friedman universe in the radiation dominated era. In such a universe, the Jeans length and the Schwarzschild radius of the mass contained within the event horizon are of the same order as the horizon radius itself. As a result, positive density fluctuations may collapse into black-holes. The mass function of those primordial black-holes depends on the primordial fluctuations spectrum and can be theoretically obtained only under particular assumptions (MacGibbon and Carr 1991). Furthermore, the mass function and density of PBH could depend on possible particle physics phase transitions affecting the state function.

In 1974, it was shown by S.Hawking (1974) that black-holes should be associated with a temperature increasing like the inverse of their mass and that they should correspondingly be responsible for the emission of a black-body-like radiation through the influence of their gravitational field on the vacuum quantum fluctuation at their horizon vicinity. The radiated power goes as the inversed fourth power of the mass according to Stefan-Boltzmann law and as the black-hole mass decreases, the Hawking-radiation output power increases.

The black-hole ends up in a violent explosion accompanied by an important γ-ray emission. Primordial black-holes reaching this state at the present time should have formed with a mass of $10^{15}g$ (Halzen 1991). The details of this explosion are mostly unknown. Some authors have suggested that a photosphere forms (Heckler 1997), processing high energy radiation to lower energies (few 100MeV). In all cases, the time scale of the explosion is driven by the particle physics at temperatures still unexplored. As the black-hole mass decreases the temperature increases and the number of particle species available for evaporation increases opening up the phase space and accelerating the explosion. Predictions are ranging from the standard model (Page and Hawking 1976) with time scales of seconds with energy peaking in the TeV domain (no photosphere) to the Hagedorn bootstrap model (Hagedorn 1970) with time scales of $\sim 100ns$ with energy peaking at 160MeV. Quite independently from the models $\sim 5 \times 10^{34} ergs$ are released in the form of γ-rays during the final explosion. Final explosions of primordial black-holes as far as 250pc could be detected. This allows to estimate the volume we would be actually probing with SGARFACE and derive the upper limit on the primordial black-hole explosion rate density we could achieve. This is shown on Figure 5 in which we assumed a field of view of 2° and 2 years of operation with a duty cycle of 10%. The dashed line is obtained if the 7 VERITAS telescopes are used in parallel. Depending on the time scale, SGARFACE individual burst fluence sensitivity of will be up to 100 times better than space based detectors like GLAST. Concerning the search for primordial black-holes, this is compensated by the much

larger duty cycle and solid angle covered by space detectors. This makes the two types of experiment very complementary and it should allow to probe for the existence of primordial black-holes at levels two orders of magnitude lower than present upper limits almost independently from the unknown particle physics at the highest energies. A detection would be the first experimental observation of Hawking radiation and would bring a unique piece of information on the early universe while, as a bonus, providing hints on the particle physics at still unexplored temperatures.

4   Conclusions

The SGARFACE experiment dedicated to the detection of sub-millisecond γ-ray burst should start operating in a prototype mode this fall and should be completed during the winter 2001-2002. The experiment should be sensitive to bursts with fluence as low as $5 \times 10^{-9} ergs.cm^{-2}$ and combined with space based experiment the existence of primordial black-holes should be probed with sensitivities unprecedented. In another direction, the very good fluence sensitivity may permit the detection of fast features in the end of a γ-ray bursts toward which the telescope would have been pointed after the reception of an alert. A detection would provide a few arc-minute location of the burst.

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