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Ground-based detection of cosmic gamma-ray bursts through atmospheric scintillation technique - A feasibility study

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Abstract. A ground-based experiment is proposed for detecting cosmic gamma-ray bursts. The underlying detection strategy and some salient features of the instrument are discussed in this paper.

1. Introduction

Although cosmic Gamma Ray Bursts (GRB) were discovered over 30 years ago and the BATSE gamma-ray burst detector, on board the Compton Gamma Ray Observatory, has, since April 1991, detected over 2000 cosmic γ-ray bursts, their nature and lineage continue to baffle even today. One of the principal reasons for this stalemated state of affairs, generally speaking, is the poor event-localization capability of the BATSE and the earlier generation of GRB detection systems (typically > a few degrees), which does not generally permit to make confusion-free searches for the burst counterparts in other regions of the electromagnetic spectrum. The picture has started changing with the successful launching of the multi-payload Beppo-Sax X-ray satellite (an Italian-Dutch project) which has on board a Gamma-Ray Burst Monitor also. In this paper, we show that a viable and cost-effective way out of this difficulty may offer itself by resurrecting the atmospheric scintillation technique, first attempted in seventies to detect short time-scale GRB postulated to accompany supernova explosions and primordial black-hole outbursts (Colgate, 1968; Rees, 1977; Razdan and Bhat, 1997).

2. Proposed detection strategy

A cosmic gamma-ray burst (GRB), generally comprising photons of energy $E_\gamma \sim$ 10's keV - 100's MeV, has a representative fluence range of $\sim 10^{-7}$–10^{-3} $erg\ cm^{-2}$ and typically lasts from a fraction of a second to hundreds of seconds. It deposits its energy in the top strata of the atmosphere (~ 50–100 km altitude), exciting and ionizing molecular nitrogen and thereby converting the deposited energy into isotropic fluorescence light with an efficiency of $\sim 3 \times (10^{-4} - 10^{-3})$ (Fazio, 1967). The resulting molecular-band emissions from the N_2^+ ion, confined essentially over the wavelength range $\lambda \sim 390 \pm 40$ nm can be picked up, in principle, by a ground-based optical detector by discriminating against uncorrelated shot-noise fluctuations induced in it by the light of night sky on a time-scale comparable with the burst duration or, better still, during the period the burst may display a major time-structure (flux-peak). By timing the arrival of the burst-induced fluorescent photons with a relative-time resolution of $\leq 10\ \mu s$, using a battery of narrow-beam fluorescent detectors, looking at the sky with averted fields, it should be possible to reconstruct the arrival direction of a GRB with an accuracy ranging from a fraction of a degree to several degrees, depending upon the burst peak flux. Triangulation with other ground-based or space-borne GRB detectors can further improve the inferred direction accuracy.

3. BEST

Based on the above concept, we have proposed the ground-based experiment BEST (Burst Exploration through ScintillationTechnique) for detecting cosmic gamma-ray bursts. The BEST is one of the 4 building blocks of the γ-ray astronomy facility GRACE, which is being established at Mt. Abu, Rajasthan, for undertaking detailed investigations over essentially the entire γ-ray spectral window from a single geographical location (Bhat, 1997). As sketched in Fig. 1, the BEST front-end instrumentation will comprise a battery of 120 detector-clusters, arranged in a circular ring of diameter ~ 10 m in the focal plane of a light-weight Aluminium (Al) mirror of 25m-diameter (*f*/1 system). A detector cluster consists of 4 closely-packed photomultiplier tubes (PMT), each of which is equipped to sample light from the night sky over the wavelength range ($\lambda \sim 350 - 430$ nm), wherein all the prominent N_2^+ fluorescent bands are found to lie. The PMT's cover mutually exclusive circular fields of view of 1 degree diameter each, thereby yielding an overall sky coverage of 0.12 str. for the 480 channels of the BEST focalplane instrumentation in so far as the GRB-induced fluorescent photons are

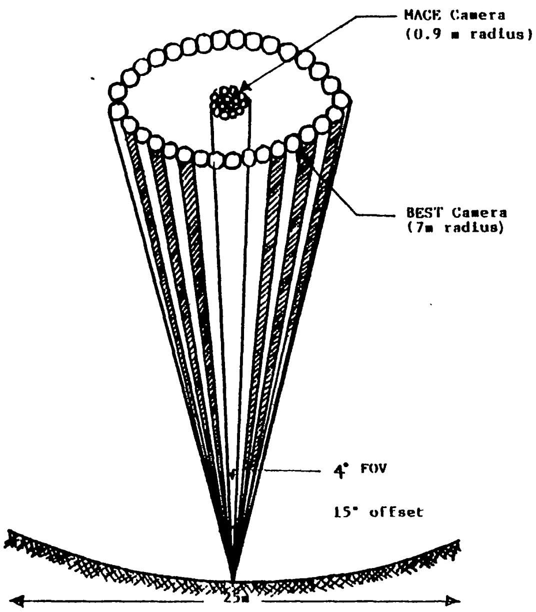

Figure 1. A schematic representation of the BEST detector array.

concerned. These photons can be produced in the atmosphere over the altitude range ~ 50 – 100 km by a gamma-ray burst incident anywhere in the upper hemisphere; thus, as far the sky coverage of the BEST for the cosmic GRB themselves, it is essentially 2 π str (as against 2.7 π str for the BATSE). The light collector area has been taken as $450m^2$ and its reflection efficient as 0.8. The light of night sky background intensity has been assumed to be ~ 3 × 10^9 photons $m^{-2}s^{-1}nm^{-1}$ and the average quantum efficiency of the PMT cathode as ~ 0.15 over the wavelength interval of interest here. The output of each PMT detector is digitized with a basic integration time of ~ $10\mu s$ and the digital datastream, thus generated, is sampled for non-Poissonian excesses on time-scales > $1ms$, compatible with the GRB durations (Fig. 2). In the event of registering such an excess in the summed output of the upto 480 BEST detector channels, the individual channel data-stream segments are passed through appropriate noise-rejection filters to facilitae recognition of a common time-profile feature in these channels. The relative differences in the arrival-time of this feature in these detector channels are then utilized, through the standard x^2-minimization procedure, to reconstruct the arrival direction of the progenitor γ-ray burst at the top of the atmosphere.

A high-definition, 400-600 PMT pixel Cerenkov light imaging camera (pixel resolution 0.15° - 0.25°, FoV=4° – 6°) is placed at the centre of the focal-plane which enables this system to function as the MACE imaging telescope for doing γ-ray astronomy in the asyet unexplored energy photon domain of ~ 10's GeV - 100's GeV (Bhat, 1997). Because of the isotropic emission property of the fluorescent light, the BEST has essentially an all-sky coverage for the GRB detection. In principle, this 'bonus' features would allow the BEST and the MACE

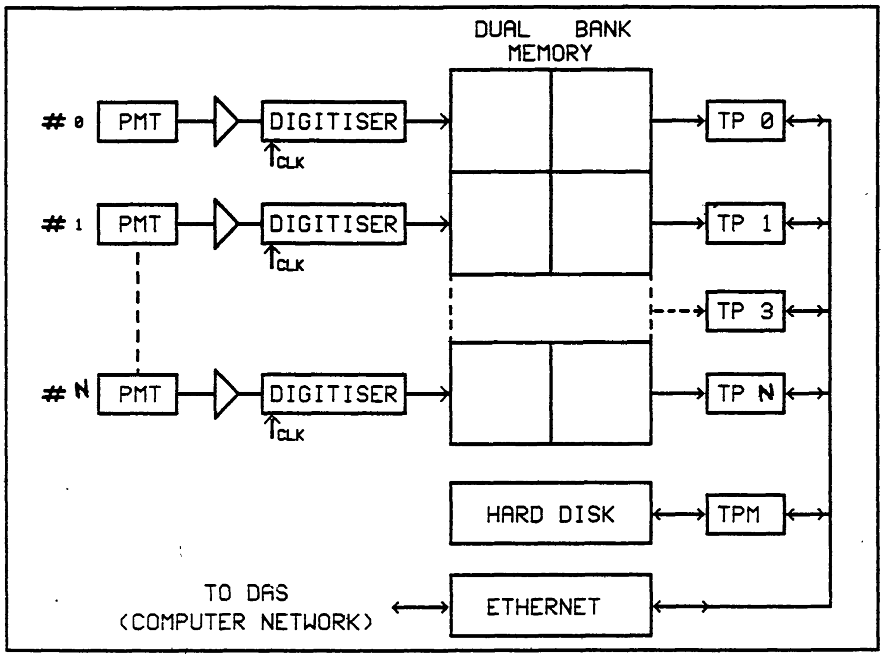

Figure 2. A block diagram of the BEST data acquisition system.

focal-plane instrumentation to be deployed concurrently to search for high energy spectral tails in cosmic γ-ray bursts from one location (Baring, 1997 and references therein).

4. BEST Salient Features

Assuming that the LONS-induced shot-noise fluctuations (noise) is the predominant background against which the GRB-excited optical fluorescent pulse (signal) with a duration of τ seconds has to be detected, the sensitivity of the BEST in the common-trigger mode (summed output of all 480 PMT channels) is $S_o \sim 3.3\times10^{-6}\sqrt{\tau}$ erg cm^{-2} for a signal-to-noise ratio of ~ 3 and for a value of ~ 0.1% for the atmospheric fluorescence efficiency η_{fl}, consistent with incident γ-ray photons having $E_\gamma \sim$ 10keV – 1 MeV (η_{fl} varies between $3\times10^{-3} - 3\times10^{-2}$ for $E_\gamma \sim$ 10's keV -100's MeV). Thus, for a burst of 1-second duration, the minimum detectable fluence or size for the BEST turns out to be ~ 3×10^{-6} *erg cm*$^{-2}$. Referring now to the BATSE 3B catalogue (Meegan et al. 1996) and accounting for the expected differences in the operational duty-cycles of the BATSE and the BEST (~30% and 15% respectively) and the respective sky-coverages of the two instruments, (~2 π sr for the BEST as against 2.7 π sr. for the BATSE), the annual average rate of detection of the GRB by the BEST turns out to be ~ 130 as against ~ 340 for the BATSE. Again, referring to the BATSE events, ~ 25% events have peak flux-to-average flux ratio (k) of ≥ 5, while ~ 65% events have $k > 2$. The corresponding peak-feature in the secondary fluorescent pulse, detected by a PMT detector, can be retrieved from the LONS-induced shot-noise fluctuations effectivley by employing random-noise rejection strategies like fast-fourier transforms. Simulation studies carried out by us so far indicate that a burst with an average flux of 5×10^{-5} *erg cm*$^{-2}$s^{-1} (10^{-4}*erg cm*$^{-2}$ s^{-1}) can give away such a peak feature with a $\pm 1\ \sigma$ resolution of ~ 14μ*s* (7μ*s*) for k=5 and 30μ*s* (15μ*s*) for k=2. Using the event-related arrival time-information from all the 480 individual detector channels, these time-jitter values translate to the GRB direction reconstruction accuracy of < 2.6° ($k \geq 2$), and 1.3° ($k > 5$) for a burst flux of 5×10^{-5} *erg cm*$^{-2}$s^{-1} and < 1.3° ($k \geq 2$) and < 0.7° ($k \geq 5$) for a flux of 10^{-4} *erg cm*$^{-2}$ s^{-1}. By using 3 BEST-like detectors with an inter-station of distance of ~ 1000 km, the direction accuracy can be further improved significantly by a factor of ≥ 5.

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