GRAVITATIONAL WAVES AND GAMMA-RAY BURSTS

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ABSTRACT.

Two experiments under way over the next few years, ARGO-YBJ and VIRGO, are optimized for the detection, respectively, of high energy tails ($10\ GeV \div 1\ TeV$) of GRBs spectra and of GW events. In this paper we discuss the opportunity of correlated observations with these two detectors in the study of GRB physics.

1. Introduction

The recent discovery of transient counterparts at X-ray, optical and radio frequencies, suggested that some and most likely all GRBs are cosmological, thus implying that their sources release $\sim 10^{51} \div 10^{53}\ ergs$ or more in a few seconds. The preferred model explains the observed γ-rays as the result of emission from an ultra-relativistic energy flow, possibly triggered by a binary Neutron Star (NS-NS) merger, converted to radiation in an optically thin region (the "fireball"). Among GRB models, this is the only one that is based on an independently observed phenomenon, is capable of releasing the required amounts of energy within a very short time scale and takes place at approximately the same rate. In fact, from BATSE data we can infer a volume burst rate of ~ 30 GRBs $yr^{-1}\ Gpc^{-3}$, comparable with the expected NS-NS merger rate of $\sim 10^{2\pm1}\ yr^{-1}\ Gpc^{-3}$ (Kochanek & Piran 1993). The possible discrepancy may imply that γ-rays are beamed (as suggested from analysis of the recent GRB990123 (Kulkarni et al. 1999)). This coalescence phenomenon has one specific observational prediction: a coincidence between a GRB and a characteristic Gravitational Wave (GW), thus allowing to verify the coalescing hypothesis. Possible scenarios have been conceived, most of them suggesting GW fluxes near the sensitivity limit of the future GW detectors. However, due to the complete novelty of this phenomenon, in the following we discuss the opportunity of correlated observations of GWs and the high energy tails of GRBs spectra using the laser interferometric detector VIRGO and the air shower array ARGO-YBJ.

2. The ARGO-YBJ experiment

The aim of the experiment ARGO-YBJ is the study of cosmic rays, mainly cosmic γ-radiation, at an energy threshold of $\sim 100\ GeV$, with a detector sampling the charged particles of atmospheric showers. Such a detector, performing a continuous high sensitivity sky survey, complements the narrow field of view (FOV) of air Cerenkov telescopes allowing to bridge the GeV and TeV energy regions and to face a wide range of fundamental issues in Cosmic Ray and Astroparticle Physics including γ-ray astronomy, GRBs physics and the measurement of the $\overline{p}/p$ at TeV energies (Abbrescia et al. 1996). The apparatus consists of a full coverage array realized with a single layer of Resistive Plate Counters (RPCs) of dimension $\sim 71 \times 74\ m^2$, surrounded by an outer ring of 28 clusters of RPCs of area 42 m^2 each, for a total area of $\sim 6500\ m^2$. The detector will be installed at the Yangbajing Laboratory (Tibet, P.R. China, 4300 m a.s.l.). The site coordinates (longitude 90° 31' 50" E, latitude 30° 06' 38" N) permits the monitoring of the Northern hemisphere in the declination band $-10^\circ < \delta < 70^\circ$. Detector assembling will start late in 2000 and data taking with the first $\sim 750\ m^2$ of RPCs in 2001.

2.1. ARGO-YBJ Sensitivity to High Energy GRBs

The observation of GeV photons by EGRET during a few intense GRBs suggested the idea that a large part of events could have a high energy component, not observed so far due to the low fluxes (Catelli et al. 1997a). Gamma-ray emission in the GeV-TeV energy range is predicted by some fireball models (see Baring 1997, for a review). The study of the high energy part of the spectrum would be of great importance to investigate the physical conditions of the emitting region, restricting the range of fundamental parameters as the magnetic field, the energy density and the bulk Lorentz factor.

Unfortunately, due to cosmological distances of the GRBs sources, the high energy γ-rays are absorbed by pair production on starlight photons during their travel towards Earth. This effect could affect the spectra at relatively low energy: according to Salamon and Stecker (1998), the flux of γ-rays of energy $E > 100\ GeV$ is strongly reduced if the distance of the source is $z = 0.5$.

If GRBs are standard candles out to $z_{max} \sim 2$, from BATSE data we expect $N_{GRB}(\geq 100\ GeV) \sim 400\ yr^{-1}$ (Mannheim et al. 1996). The ARGO-YBJ aperture angle for low energy showers ($\sim 40^\circ$) implies a FOV of ~ 1.5 sr, therefore in this solid angle we expect ~ 40 GRBs yr^{-1} with spectra extending at energies $> 100\ GeV$. But the number of GRBs which can be detected depends on the instrumental sensitivity, the spectral shape and the duration of the bursts. A GRB with a power-law energy spectrum $dN/dE \propto E^{-\alpha}$ and a time duration Δt, is detectable by ARGO-YBJ if the energy fluence in the energy range $1\ GeV < E < E_{max}$ is larger than a given value F_{min}, with $E_{max} > 10\ GeV$. This assumption is supported by EGRET observations, which report power-law spectra extending with no visible cutoff up to the maximum energy determined by the instrument sensitivity (in some cases above 1 GeV). The average spectral slope observed in the $30\ MeV \div 10\ GeV$ region is $\alpha = 1.95 \pm 0.25$ (Dingus et al. 1997). Fig. 1 shows F_{min} vs. E_{max} for a GRB duration $\Delta t = 1\ s$ and a spectral slope: $\alpha = 2$. The minimum fluence for a different duration Δt scales as $\sqrt{\Delta t}$. The minimum required statistical significance of the signal is $\sigma = 4$ standard deviations. The two lines refer to different operation modes of the detector (see Bacci et al. 1999 for details).

To compare the ARGO-YBJ sensitivity with the fluxes that can be reasonably expected at high energy, in the same figure we report the fluences in the $1 \div 100$ GeV energy range obtained extrapolating (with the observed slopes) the spectra measured by EGRET during the events detected by the TASC instrument (Catelli et al. 1997b). As can be seen in the figure, most of the events have an energy fluence larger than the ARGO-YBJ limits.

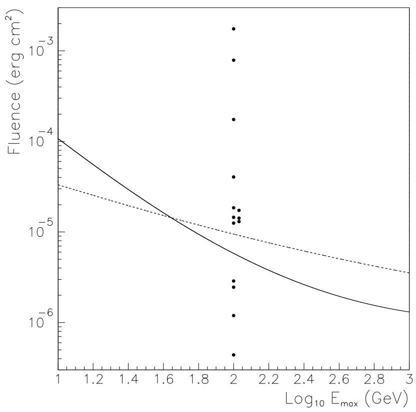

Fig. 1. Minimum energy fluence F_{min} in the $1 \div 100$ GeV range observable by ARGO-YBJ as a function of the maximum energy of the specrum E_{max}. The points represent the extrapolations to 100 GeV of 14 EGRET spectra.

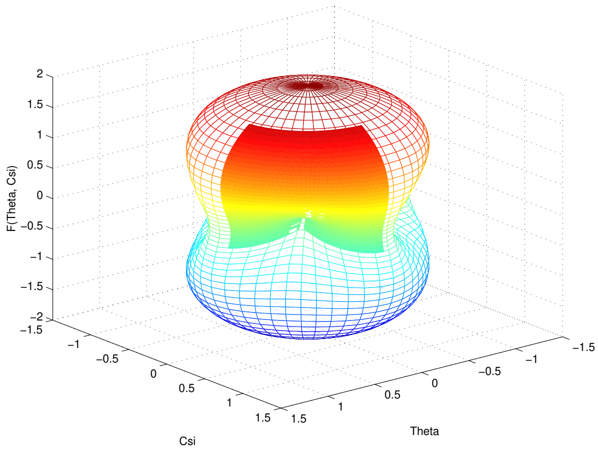

Fig. 2. Polar diagram illustrating the ARGO-YBJ/VIRGO common FOV (filled area). The principal axes on the $\xi - \theta$ plane are oriented along the interferometer arms.

3. The VIRGO experiment

As an Italian-French collaboration project, the VIRGO experiment consists in an interferometric long baseline antenna for the detection of GWs over a broad frequency range (from 10 Hz to 10 KHz). The antenna is basically a Michelson interferometer: the physical arm length is 3 km and it is enhanced to the equivalent length of 120 km by using Fabry-Perot cavities in each arm. The interferometer will be illuminated by a 20 $Watts$ ultra-stable Nd-YAG laser. The planned interferometer sensitivity in the low (and most interesting) frequency region will be reached by isolating the optical component with a Super Attenuator of sismic noise. The planned sensitivity is $\tilde{h} = 10^{-21}/\sqrt{Hz}$ at 10 Hz and $\tilde{h} = 3 \cdot 10^{-23}/\sqrt{Hz}$ at 500 Hz. The scientific goals are the study of general relativity in the still poor known strong gravitational regime by means of the first direct detection of gravitational radiation, and the deeper observation of astrophysical sources like coalescing binary Neutron Star systems, SuperNovae explosions, rotating Pulsars and Black Holes (Bradaschia et al. 1995). The experiment will be installed in Cascina, near Pisa (Italy), and is planned to be operative during year 2002.

3.1. VIRGO Sensitivity to Coalescing Binaries

Coalescing binaries in distant galaxies are one of the most promising sources of detectable gravitational radiation. Recently a multistep procedure for the on-line detection and analysis of GW signals emitted during the coalescence of compact binaries has been proposed. This procedure is based on Adaptive Line Enhancers filters and a fast off-line parametrization, using the controlled random search optimization algorithm (Milano et al. 1997). The results of simulations show that it is possible to reach a strain sensitivity, integrated on the duration of the signal, of $h_i \sim 10^{-23}$ even considering signal duration of a few seconds. This would allow a considerably extension of the detection limit for coalescing binaries, up to $\sim 500\ Mpc$. From the estimated NS-NS merger rate, we expect that VIRGO can detect up to ~ 500 mergers per year at distances $\leq 500\ Mpc$.

4. Correlated ARGO-YBJ/VIRGO observations

The ARGO-YBJ/VIRGO coincidence rate depends, besides the respective sensitivities, on the common FOV showed in Fig. 2. Due to the different site of the two experiments the overlapping region is centered on a non-ideal direction for the VIRGO interferometer; therefore the signal is decreased with respect to the ideal case giving a rate lower by a factor ~ 10. For sake of simplicity, owing to the large FOV of the VIRGO detector, we can assume that the common FOV of the two experiments is limited by the ARGO-YBJ aperture angle. Therefore, according to current statistics, the number of GRBs expected in the FOV of ARGO-YBJ, from distances up to 500 Mpc, is about one per year.

Therefore, one may look with moderate optimism into the future of correlated studies of GRB physics by means of the ARGO-YBJ and VIRGO experiments.

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