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Joint searches for gravitational waves and high-energy neutrinos

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Abstract. Many of the astrophysical sources and violent phenomena observed in our Universe are potential joint emitters of gravitational waves and high-energy cosmic radiation, in the form of photons, hadrons, and also neutrinos. This has triggered a collaborative analysis project between gravitational wave detectors and high-energy neutrino telescopes. In this article, we review some of the motivations for having pursuing science jointly and present the effort's status.

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1. Introduction

This article reports the status of an on-going project [1, 2, 3] aiming at the joint detection of gravitational waves (GW) and high-energy neutrinos (HEN). GWs and neutrinos are similar in several ways. They are not absorbed[‡] nor diffused by the interstellar medium or background radiation as opposed to high-energy photons. They are not deflected by extra-galactic magnetic fields as opposed to charged cosmic rays, so that the source location can be traced back from the direction of arrival. They interact weakly with the environment so that they can escape very dense media. Thanks to these properties, GW and HEN are both able to convey information from the core of the most violent astrophysical events in the Universe.

The basic motivation for the joint search of GW and HEN is the existence of potential common sources. In Sec. 2, we list those sources. We give a short description of the detectors involved in this project and examine the feasibility of the joint search in Sec. 3. In Sec. 4, we report on the development of the data analysis strategies.

2. Potential common cosmic sources of GW and HEN

Several conditions have to be met for an astrophysical object to yield significant emission of both GW and HEN. To generate GW, this object has to be compact (i.e, a massive and dense distribution of matter), and display a relativistic bulk motion. In order to be detectable by LIGO or Virgo, the periodic (i.e., orbital or spinning) or transient motion has to be characterized by a typical time-scale of order of tens of milliseconds, compatible with the detector sensitive frequency band. This must be accompanied by the ejection of relativistic baryons for the production of HENs. The astrophysical objects that satisfy those requirements include Galactic (e.g., connected to Soft Gamma Repeaters [4, 5] during their flaring episodes) and extra-Galactic associated to Gamma-Ray Bursts (GRBs). We will only discuss the latter in the following.

2.1. Gamma-ray bursts

Gamma-ray bursts (GRBs) are intense flashes of gamma-rays (see e.g., [6] for a recent review). They are associated with an exceptional energy release in the electromagnetic spectrum with an equivalent isotropic emission of order $E_{EM}^{iso} \sim 10^{50} - 10^{52}$ erg within a few seconds to few tens of seconds. GRBs are the most luminous events in the Universe observed up to today. They are observed to be isotropically distributed and usually located at cosmological distances.

The *fireball model* (see [7] for a review) provides a widely accepted phenomenological picture that accommodates the observations. A central engine ejects blobs of plasma at relativistic speeds. The inhomogeneities in the jet form shells that can propagate at different speeds. The shells collide eventually and electrons get accelerated during

[‡] Strictly a very small fraction of the cosmic neutrinos is absorbed by the interstellar medium.

those shocks. They release their energy by producing synchrotron and inverse Compton γ s which are finally observed as a GRB. If protons are also present in the jet, their interaction with the synchrotron photons can produce pions through the Δ -resonance whose decays produce (muon and electron) neutrinos. The production of such a burst of HENs would therefore be intimately related to that of the GRB [8].

There are two types of GRBs, phenomenologically distinguished by their duration. The short ($T \lesssim 2$ s) and long GRBs ($T \gtrsim 2$ s) are associated with different progenitors. The central engine of the former is thought to be a merger of neutron-star–neutron-star or black-hole–neutron-star binary systems [9], while there are indications that the latter is connected to the collapse of spinning massive star to a black-hole (so-called “collapsar” scenario [10]). Both are expected to be sources of GW bursts [6].

“Failed” GRBs — The fireball model has been successful in explaining a large fraction of the observations. There are however suspicions that the above mentioned process can sometimes follow a different path. To understand possible alternative scenarios, some insight into the physics of the fireball is needed. We need to explain why the GRB jets have to be ultra-relativistic, an issue that is usually referred to as the “compactness problem” [7].

Above a given critical energy, high-energy γ interact with photons of lower energies and form electron-positron pairs. The optical depth for this process can be shown to be $\propto f_p/R_e$ where f_p is the fraction of the photon pairs which satisfy the $e^- - e^+$ formation condition and R_e is the radius of the emission region. Ignoring relativistic effects, it is estimated to be of order 10^{13} for a typical GRB, by far too large for any photon to escape and hence the GRB to be observed. Relativistic effects blue-shift the photon energy (less photon pairs satisfy the pair formation condition, hence reducing f_p) and allow to stretch R_e (which is deduced from the observed time variability of the GRB) by a substantial factor. The net result is the reduction of the optical depth by a factor of $\Gamma^{4+2\alpha}$, with Γ the Lorentz factor, and $\alpha \approx 1$ to 2 the spectral index for high-energy photons [7]. The jet becomes optically thin for ultra-relativistic jets with $\Gamma \sim 100$ which is thus a requirement for the observation of GRBs.

Baryonic mass slows down the flow. Too much of it prevents the jet to be ultra-relativistic [7]. A slight baryonic pollution results in mildly relativistic jets with $\Gamma = O(1)$. In that case, the jet is optically thick and no GRB is observed. This scenario is usually referred to as “failed” GRB [11]. While the GRB does not occur in this case, GW and HEN emission remain.

The observation of such objects with conventional telescopes is challenging and GW and HEN provide an alternative. Although the rate of such events is unknown, it could be large [11] with a potential connection with the putative local under-luminous population of GRBs.

§ Here, γ refers to photons with energies in the gamma and hard X-ray parts of the electromagnetic spectrum.

3. Presentation of the detectors and feasibility of a joint GW and HEN search

The large-scale interferometric GW detectors Virgo and LIGO and the HEN telescopes ANTARES and IceCube are involved in a joint search project. For the sake of completeness, we present briefly the partner HEN telescopes. For more details, we refer the reader to the specific presentations included in these proceedings [12, 13].

Presentation of the HEN telescopes — ANTARES and IceCube are large-scale arrays of photo-multipliers connected to strings which instrument a large volume of sea water or ice. IceCube (located at the geographic South pole) is larger in size than ANTARES. The detector will reach the km^3 scale when completed with 80 strings. With 22 strings, ANTARES (located in the Mediterranean sea, near Marseilles) is a large-scale demonstrator for a future European km^3 detector in sea water.

Those detectors follow the same principle: a cosmic neutrino interacts with the detector environment and forms a relativistic muon. When the muon enters the water or ice, it generates a flash of Cerenkov light. This signature is detected by the optical modules if it occurs within the detector. The detection of the muon and the reconstruction of its track is based on local coincidences of the light hits compatible with the Cerenkov light front. Thanks to this detection principle, it is possible to detect neutrinos in the energy range above few tens of GeV. The typical reconstruction accuracy is about a degree with some difference whether ice or sea water is used.

The detectors are optimized to look downward. There is a large background coming from above associated with muons from cosmic-ray air showers and to a lesser extent from below due to the atmospheric neutrinos generated by the same process. The detection of cosmic neutrinos is thus possible only in the hemisphere opposite to upward-pointing vertical at the detector with an instantaneous sky coverage close to 2π sr. The location of ANTARES provides an annual sky coverage of about 3.5π sr, covering the Southern hemisphere and the Galactic center. The complementary IceCube detector is observing the Northern hemisphere, with full acceptance of 2π sr for the considered energy range (from a few tens of GeV to 100 TeV).

Because of the presence of background (due to atmospheric neutrinos and misreconstructed downward-going muons), the observation of an anisotropy in the directions of arrival or of a very energetic candidate event (with energy much larger than that of background) is required to differentiate it from background. A third possibility is the use of multi-messenger astronomy as discussed in Sec. 4.

Search feasibility — ANTARES and IceCube are operational and have been taking data during the last years in partial configurations. Several data sets overlap with the LIGO-Virgo science runs S5-VSR1 and S6-VSR2. It is likely that there will be more in the future as the program of upgrades appears nicely synchronized.

All the ingredients are joined together to make the search viable: there is a good

sky coverage thanks to the complementarity of ANTARES and IceCube. Their sky coverage significantly overlaps with that of the GW detectors. The overlap is estimated to be roughly ~ 4 sr (~ 30 % of the sky) || for each HEN telescope.

4. Development of the data analysis strategy

Investigations of the search feasibility have been performed [1, 2] with simulated data. The fundamental rationale for the coincidence search is that we are dealing with independent detectors, based on radically different physics but targeting the very same cosmic sources. The probability of an accidental time *and* spatial coincidence due to background can be set to very small value.

The results obtained for a hypothetical IceCube-LIGO network [1] and an IceCube-LIGO-Virgo network indicate that even if the individual observatories in the network provide several triggers a day, the false alarm rate for the combined detector network can be very low (e.g., $\sim 1/(500$ yr) for a network composed of the two LIGO detector and IceCube assuming a 1 second coincidence window).

The width of the time and spatial coincidence windows are particularly important ingredients. The uncertainties in the source model largely dominate the timing accuracy of each instrument. The width of the time coincidence window is thus determined by the maximum time delay between GW and HEN emission. In the case of GRBs, the production of HENs and γ are both expected to be comparable to the fireball lifetime. We can thus use gamma-ray observations to deduce the time delay [14]. As pictured in Fig. 1, the analysis of $\sim 10^3$ GRBs in the 4th BATSE catalog [15] shows that in 95% of the cases, the light curve has a duration T_{90} shorter than 150 seconds. Including the possibility of precursors (observed for a fraction of the GRBs), the worst cases where GW and HEN triggers are the most separated in time define the following time coincidence $[-350s, +200s]$.

The spatial coincidence window is essentially related to instrumental limitations. The error box for the reconstruction of the source sky position has been shown to be ~ 10 square degrees for GWs [16, 17] and \sim square degrees for HEN [13, 12] with some dependency upon the characteristics of the event. Simulations are on-going to determine these more systematically and more precisely. We expect that the lowering of event selection threshold (allowed by the joint analysis) will worsen the average sky resolution.

The detailed architecture for the joint analysis pipeline is not completely defined. In addition to the approaches considered in the early works mentioned above [1, 2], we will explore the potential of the pipelines normally used for externally triggered searches (see [18] and references therein) such as the X-pipeline [19].

|| The sky is considered “visible” to GW detectors where the combined antenna pattern is above the half-maximum.

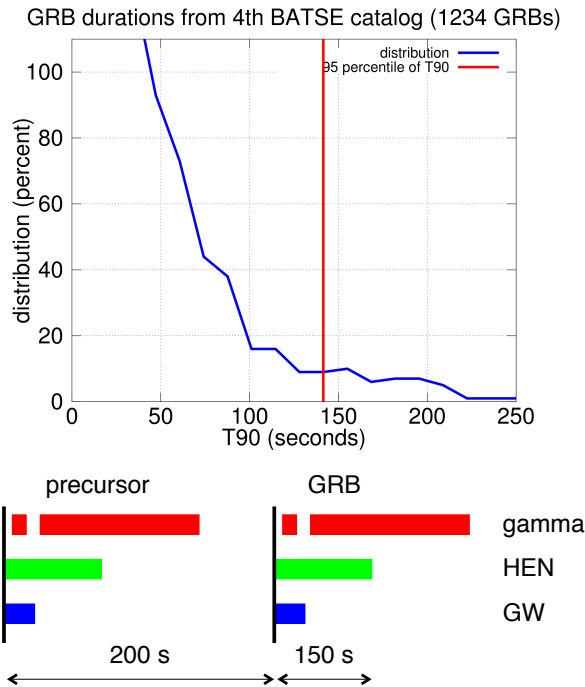


Figure 1. Time delay between GW and HEN — (top) This plot displays the distribution of the GRB duration taken from the 4th BATSE catalog. The duration of a GRB is thus determined to be shorter than 150 seconds with 95% confidence. (bottom) This figure shows the different components of the time delay between gravitational wave and high energy neutrino signals. Based on the available results, we cannot exclude the possibility of being able to detect GW, as well as HEN signals both from the precursor and the main GRB event. The resulting time coincidence window is $[-350s, +200s]$.

5. Concluding remarks

A collaboration between GW and HEN observatories has been started. A dedicated workshop held in Paris in May 2009 [20] provided a first occasion for the two scientific communities to meet and define a common plan. The working group joining GW and HEN contributors met face to face for the first time in Rome just before the GWDAW-14 workshop. Data exchange agreements have been signed by the involved parties allowing the more detailed definition of the joint data analysis procedure. In five to ten years from now, large improvements of the sensitivity and reach are likely both for the observations in GW and HEN channels. The project presented here is an important pioneering effort with existing data and a crucial path-finder effort for this “advanced” detector era.

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