Joint searches of 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 emitters of gravitational waves and high-energy cosmic radiation, in the form of photons, hadrons, and presumably also neutrinos. This has triggered a collaborative analysis project between gravitational wave detectors and high-energy neutrino telescopes. In this article, we review the motivations for having this joint project and present its status.

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1. Introduction

This article reports the status of an on-going project aiming at the joint search of gravitational wave (GW) and high-energy neutrinos (HEN). GWs and HENs 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 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.

In Sec. 2, we list potential common sources of GWs and HENs. 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 the first steps toward a complete definition of the data analysis strategy.

2. Potential common 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 a massive and dense distribution of matter with a relativistic bulk motion. The periodic (i.e., orbital or spinning) or transient motion has to take place over a time scale of order of tens of milliseconds, compatible with the LIGO and Virgo 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 includes Galactic (e.g., connected to Soft Gamma Repeaters [1, 2] during their flaring episodes) and extra-Galactic associated to Gamma-Ray Bursts (GRBs). We will mainly discuss the latter in the following.

2.1. Gamma-ray bursts

Gamma-ray bursts (GRBs) are intense flashes of γ-rays (see e.g., [3] 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 few seconds to few tens of seconds. GRBs are the most luminous events in the Universe. They are observed to be isotropically distributed and located at cosmological distances.

The *fireball model* provides a widely accepted phenomenological picture that accommodates the observations. A central engine shoots blobs of plasma at relativistic speeds. The inhomogeneities in the jet form shells that propagate at different speeds. The shells collides eventually and electrons get accelerated during those shocks. They release their energy by producing synchrotron γ-photons 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 decay produces (muon and electron) neutrinos. The production of the burst of HENs is therefore intimately related to that of the GRB.

There are two types of GRBs, distinguished by their duration. The short ($T \lesssim 2$ s) and long GRBs ($T \gtrsim 2$ s) are associated with different progenitors. For the former, the central engine is thought to be mergers of neutron-star–neutron-star or black-hole–neutron-star binary while there are indications that the latter is connected to the collapse of spinning massive star to a black-hole (so-called "collapsar" scenario). Both are expected to be sources of GW bursts [3].

"Failed" or "Choked" GRBs — The fireball model has been successful in explaining the observations. There are however suspicions that the the above mentioned process may follow a different path.

To understand the 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" [4].

Above a given critical energy, high-energy γ photons 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, too large for 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 index of high-energy photon spectrum. The jet becomes optically thin for $\Gamma \sim 100$.

Baryonic mass slows down the flow [4]. Too much of it prevent the jet to be ultra-relativistic. A slight baryonic pollution results in mildly relativistic jet 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 [5].

The observation of such objects with conventional telescopes is more challenging and GW and HEN provide an interesting alternative. Although the rate of such event is unknown, it could be large [5] with a potential connection with the putative local under-luminous population of GRBs.

3. Experimental set-up and feasibility of a joint GW and HEN search

The large-scale interferometric GW detectors Virgo and LIGO (see [`cite status talk in GWDAW-14 proceedings`] for a status) 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 [6, 7].

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 in larger in size than ANTARES. The detector should 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 follows the same principle: a cosmic neutrino interact with the detector environment and form a relativistic muon. When the muon enter 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 coincidence of the light hits compatible with the Cerenkov light front. Thanks to this detection principle, it is possible to detect neutrino in the energy range above the TeV. 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 extend 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-going vertical at the detector. 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 mis-reconstructed 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 decide a detection. 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 visibility maps significantly overlap with that of the GW detectors. The overlap is estimated to be roughly ~ 4 sr (~ 30 % of the sky) ‡ for each HEN telescope.

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

4. Development of the data analysis strategy

Preliminary investigations of the search feasibility have been performed [8, 9] with simulated data. The rationale for the coincidence search is that we are dealing with independent detectors, based on radically different physics. The probability of an accidental time *and* spatial coincidence due to background can be made very small.

The results obtained for a hypothetical IceCube-LIGO network [8] and an IceCube-LIGO-Virgo network indicate that even if the constituent observatories provide several triggers a day, the false alarm rate for the combined detector network can be very low (e.g., $\sim 1/(600 \text{ yr})$).

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 photons are both expected to be comparable to the fireball lifetime. We can thus use gamma-ray observations to deduce the time delay [10]. As pictured in Fig. 1, the analysis of $\sim 10^3$ GRBs in the 4th BATSE catalog [11] 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) and considering the worst case where GW and HEN triggers are most distant, we end up choosing 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 have been estimated to be $\sim$ 10 square degrees for GWs and $\sim$ square degrees for HEN 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 [8, 9], we explore the potential of the pipelines normally used for externally triggered searches such as the X pipeline [12].

5. Concluding remarks

A collaboration between GW and HEN observatories has been initiated. The working group joining GW and HEN contributors met 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 path-finder effort for this “advanced” detector era.

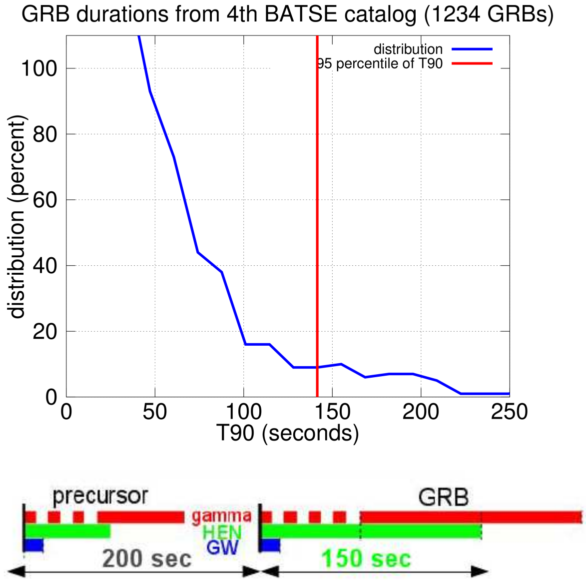

Figure 1. Time delay between GW and HEN — (top) This plot displays the distribution of the GRB duration taken from the 4th BATSE catalog. The duration of a GRB is thus determined to be shorter than 150 seconds with 95% confidence. (bottom) This figure shows the different components of the time delay 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 $[-350s, +200]$.

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