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Searches for gravitational-wave events in coincidence with γ events

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Summary. — In this paper we report about the status and prospects of the search for gravitational wave events in coincidence with γ-ray burst events in data from LIGO and Virgo detectors.

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1. – Introduction

The infall of mass into gravitational wells is a very efficient mechanism for releasing energy [1], second only to matter anti-matter annihilation, and is therefore candidate to explain some of the most violent phenomena in the Universe, like the Gamma Ray Bursts (GRB). In particular, it is believed that short GRB could be primarily associated with the coalescence of a neutron star (NS) with another compact object, like another NS or a black hole (BH) [2]. A fraction of short GRB could also be associated with soft gamma repeaters (SGR) [3,4]. On the other hand, several nearby long GRB have been correlated with core-collapse supernovae [5].

The coalescence of compact objects is known to be caused by the emission of gravitational radiation, which drives the evolution of the binary, causing the degradation of the orbital radius as in the famous Hulse-Taylor binary pulsar [6], leading eventually to the merger of the system. Also the collapse of massive stars is expected to be associated with gravitational waves (GW), which result whenever mass distributions exhibit a time-varying quadrupole momentum [1].

The direct detection of GWs emitted by such events could contribute significantly to our knowledge of the source physics; it would shed light on the details of the "engine" powering the γ emission, first of all confirming or ruling out the progenitor scenarios. Then information about the equation of state of the nuclear matter could be derived [7], in addition to test general relativity in the strong field regime [8].

The realization of km-scale GW detectors, like the LIGO [9] and Virgo [10] interferometric instruments, which have been operating for a few years now at design sensitivity, has made it possible to start searching for such correlations. No detection has been reported until present; this is consistent with current estimates of the signal strength and frequency, for instance for binary coalescences accessible to first-generation instruments [11]. The same estimates predict that a sizable number of events will instead be accessible to second-generation detectors, whose realization is just started.

2. – LSC and Virgo search strategy

The US LIGO detectors [9], and the French-Italian Virgo detector [10], form a worldwide network of instruments of comparable sensitivity; during S5-VSR1 runs, four interferometers were operated at three sites: 4 km (H1) and 2 km (H2) LIGO detectors at the Hanford (WA) site; 4 km (L1) LIGO detector at the Livingston (LA) site, and a 3 km Virgo detector at the Cascina (IT) site. The simultaneous operation of several instruments at different locations allows for a dramatic reduction of the noise background, by requiring tight coincidence of candidate events, and permits also an approximate reconstruction of the source location [12], thus making it possible to effectively operate the network as an astrophysical instrument. Individual km-scale interferometric detectors have in fact almost no directionality, and might be likened to "microphones" rather than to "telescopes"; this analogy is actually quite close to reality, since the maximum sensitivity of these instruments is in the audio band, from a few tens of Hz up to several kHz. The resulting continuous stream of audio data, which in first approximation could be represented as colored, Gaussian noise, is subject to several steps of analysis; data are calibrated [13], data quality cuts are applied to reject stretches of data contaminated by extra noise [14], search algorithms are applied to select potential candidate events, tests on signals' internal consistency, on time coincidence and amplitude consistency are performed, and further checks are carried out on any high-significance surviving event [15,16]. This general strategy is further specialized depending on the kind of signals searched; in general, matched filtering can be used for modeled signals, like the inspiral portion of a binary coalescence [17], or the ringdown signal emitted by an excited compact object. Instead, template-less methods are exerted to look for signals, generally of short duration, whose shape is *a priori* not known. When searching for events correlated with γ-ray bursts, the search can be restricted to portions of data centered on the time of the event as determined by optical instruments; typically an "on-source" segment is defined, which potentially can be affected by the GW signal, and an "off-source" segment of similar noise characteristic is exploited to estimate the background.

3. – Recent results

The LIGO Scientific Collaboration and Virgo Collaboration most recent published results, when searching for events in coincidence with GRB events, have been obtained analyzing data from LIGO's S5 run and Virgo's VSR1 runs, which collectively spanned the period from November 4, 2005 to October 1, 2007. During this period, X-ray and γ-ray instruments identified a total of 212 GRB events, mostly from the Swift satellite [18], but several from other IPN satellites [19]. Of this sample, 137 events had well-defined positions, and in correspondence of their timing the LIGO-Virgo network had at least two interferometers with science data of good quality. All these events have been analyzed for the occurrence of simultaneous candidate GW events using a "burst" pipeline [20], while a sub-sample of 22 GRBs, clearly identified as short bursts, has been also analyzed with an "inspiral" pipeline [21], covering a range of parameters sensitive to systems with total masses $2M_\odot < m_1 + m_2 < 40M_\odot$.

In both cases, no evidence was found for a gravitational-wave signal in coincidence with any GRB in the sample, and the searches resulted in upper limits; for instance, assuming an isotropic emission of circularly polarized gravitational waves with an energy of $0.01M_\odot c^2$, at the frequency of maximum sensitivity of LIGO and Virgo (150 Hz), the 90% confidence level (CL) lower limits on the distance for each GRB spanned a range up to $D = 30\,\text{Mpc}$, with a median $\tilde{D} \sim 12\,\text{Mpc}$.

Analogously, estimates for exclusion distances were obtained by the inspiral search for binary NS, resulting in a median value $\tilde{D} \sim 3.3\,\text{Mpc}$, and for pairs BH-NS, with $\tilde{D} \sim 6.7\,\text{Mpc}$.

The lack of detections is therefore not surprising; for instance, while there are few redshift determinations for short GRBs, it appears that their distribution is peaked around $\langle z \rangle \sim 0.25$ [2], corresponding to $D \simeq 1.2\,\text{Gpc}$ for current values of the Hubble constant. The smallest measured redshift in the sample was for the GRB 060614, having $z = 0.125$, corresponding to $D \simeq 578\,\text{Mpc}$.

While seemingly a desperate search at current sensitivities, it is worth underlining that approximately 70% of the GRB's in our sample has no measured redshift, hence it cannot be excluded that one or more could be closer than the typical 1 Gpc distance. We recall also that, outside our sample, there exist examples of closer events: for instance the GRB 980425 [22] had $z \simeq 0.085$, corresponding to $D \simeq 36\,\text{Mpc}$.

In the sample considered for these searches, it is also present an event, the GRB 070201, which had been already considered in an earlier search by the LIGO Scientific Collaboration [23]; its interest is derived from the possible spatial association with M31, a galaxy only 780 kpc away. Had this event been due to a coalescing binary, it would have been easily detected by LIGO instruments. The search could exclude, at a CL $> 99\%$, a binary coalescence in M31, thus lending support to the hypothesis of a soft gamma repeater [24].

The LIGO Scientific Collaboration and Virgo have also searched for gravitational wave bursts emitted by six magnetars [25], in data collected between November 2006 and June 2009 by LIGO, Virgo and GEO600 [26] detectors. No evidence of GW signals was found in correspondence of a sample of 1279 electromagnetic triggers, and it was possible to set (model-dependent) upper limits on the amount of energy emitted in gravitational waves, particularly stringent for one of the magnetars, SGR 0501+4516, which is likely at $\sim 1\,\text{kpc}$ from Earth; it was possible to assert that energy emitted in f-mode ringdown at 1090 Hz is less than $\simeq 1.4 \times 10^{47}$ erg, a limit approaching the level of electromagnetic energy emitted in SGR giant flares.

4. – Future prospects

The LIGO Scientific Collaboration and the Virgo Collaboration are currently analyzing data at higher sensitivity, collected during the LIGO S6 (7 July 2009–20 October 2010) and the Virgo VSR2 (11 August 2010–20 October 2010) runs.

Several improvements in the analysis have been developed; for instance, searches for coalescing binary events can now look for more massive systems, for which a model of the final stages of the coalescence, beyond the "inspiral" phase, is important to detect the signal in the noise background.

The Collaborations are also developing very low latency analysis pipelines, capable of identifying potential gravitational wave candidates within minutes after data collection. This opens the way to GW detectors issuing alerts allowing to point telescopes in order to search for electromagnetic counterparts. Such a low latency search has been running during S6-VSR2/VSR3 run [27].

In the meanwhile, the construction of a 2nd generation of detectors, Advanced LIGO (aLIGO) and Advanced Virgo (AdV), has started; these machines constitute a major upgrade of current instruments, improving over their amplitude sensitivity by a factor of 10 on the whole bandwidth. At fixed source strength, a tenfold increase in the range will result, thus boosting the observed volume and the event rates by a factor 1000.

These advanced detectors should start taking data in 2015 and will gradually ramp up their sensitivity and duty-cycle; once achieved the target sensitivity, the resulting advanced LIGO-Virgo network will become able to detect coalescences of binary blackholes at $\sim 1\,\mathrm{Gpc}$, and should identify several tens of NS-NS coalescences per year [11]; although such estimates are still uncertain and could vary by a factor 10 towards more pessimistic or optimistic values, there is good hope that these new instruments will mark the birth of gravitational astronomy.

5. – Conclusions

The LIGO Scientific Collaboration and the Virgo Collaboration have carried out several searches for gravitational waves in coincidence with γ-ray bursts; no evidence for GW events was found, a result fully consistent with our current understanding of the source GW emission mechanisms and of the available estimates on source distances.

In a few years advanced LIGO and Virgo detectors will be operating and will gradually ramp up their sensitivity, extending the observed volume eventually by a factor 1000. We hope that these new instruments will provide data as exciting as those now routinely produced by γ observatories and other instruments looking at other bands of the electromagnetic spectrum.

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