Prospects about X- and gamma-ray counterparts of gravitational wave signals with INTEGRAL

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Abstract. By extrapolating the number of detections made during the first LIGO science run, tenths of gravitational wave signals from binary black hole mergers are anticipated in upcoming LIGO Virgo science runs. Finding an electromagnetic counterpart from compact binary merger events would be a capital achievement. We evaluate the ability of current wide-field X- and gamma-ray telescopes aboard INTEGRAL to find such counterparts thanks to an end-to-end simulation for estimating the fraction of the sources that can be followed up and/or detected.

On September 14, 2015, the two LIGO interferometers realized the first direct detection of gravitational waves (GW). A next step would be to associate an electromagnetic (EM) counterpart to a GW event. We address the question of the joint detectability of GW events by Advanced LIGO, and associated EM events at high-energies by the INTEGRAL mission. This study is similar to that of (**?**) done with Fermi.

Monte-Carlo simulation of gravitational-wave events from neutron-star binary mergers

We produced a simulated catalogue of 6 millions Milky Way-like galaxies distributed to $z \sim 0.12$. To those galaxies, we associate binary neutron star (BNS) mergers with mass distribution and rate $R = 23.5\mathrm{Myr}^{-3}$ per galaxy according to Model A (solar metallicity) of (**?**). This results in a population of 14 000 mergers for a 100-year simulation.

The GW signals corresponding to the binary mergers was simulated using the `TaylorT4` model and injected into Gaussian noise coloured according to best sensitivity curves anticipated for the 2nd LIGO/Virgo run O2 (**?**). We distribute those events randomly in time over the expected period of O2 from Nov 2016 to May 2017. We recover the signal with a simplified matched-filtering algorithm(**?**) in the case of the LIGO-only two-detector network, and that of the LIGO-Virgo three-detector network. We select the GW events with $\mathrm{SNR}_{\mathrm{combined}} > 9$ corresponding to a false-alarm rate FAR < 1/month. With this selection cut, BNS merger can be recovered down to an horizon distance of about 150 Mpc and 50 Mpc for the LIGO and Virgo detectors respectively. This results in 170 (resp. 192) selected BNS merger signals over 100 years which corresponds to ~ 1 mergers over the 6-month duration of O2.

We recover GW signals using matched-filtering techniques and reconstruct the posterior skymaps giving the position of the source using the BAYESTAR pipeline (**?**). With two detectors, the position uncertainty is contained in a window of 700-2100 square degrees, while with three detectors, it is appreciably diminished to a 300-1700 square-degree window. The latter estimate is obtained using the 70 % fraction of events where the position estimation converged.

Electromagnetic emission model from neutron-star binary mergers

Compact binary mergers involving at least one neutron star are considered to be plausible progenitors of short gamma-ray bursts (GRB). Short GRBs is a subset of the whole GRB population with duration shorter than ∼2 seconds. Short GRBs have also a harder spectrum. Prompt emission is attributed to dissipation within the collimated ultra-relativistic jet and is therefore strongly beamed. It is followed by slowly decaying afterglow, observed from radio to GeV, produced by the interaction between the ejecta and the ambient medium surrounding the GRB progenitor. Afterglow emission is originally also strongly beamed, but as the outflow decelerates, the emission becomes progressively more isotropic.

In our simulation we assume that every BNS merger is associated with a short gamma-ray burst. We simulate synthetic prompt GRB and a hard X-ray afterglow, assuming the following simplified model.

Prompt emission

We model the prompt emission spectrum by the cut-off power-law model. This model is a variant of the Band model (**?**) where high-energies have been suppressed because they are generally not well constrained by the observations. For simplicity we assume the same prompt emission spectrum for all synthetic GRB, with $\alpha_{\mathrm{BAND}} = -0.5$ and $E_{\mathrm{peak}} = 600$ keV, close to the average short GRB spectrum observed by Fermi/GBM (**?**). We also assume fixed duration of the prompt emission of 1 s and fixed isotropic equivalent luminosity of 10^{50} erg cm^{-2} s^{-1}.

The principal source of uncertainty on rate of GRB detections associated with the BNS mergers is the beaming factor of the prompt emission. We assume a fixed beaming angle of 10 degrees. This angle is roughly compatible with the observations of the total short GRB rate inferred from our BNS population.

Hard X-ray afterglows

Although afterglows in the hard X-rays are rarely observed, it is not unreasonable to assume that they are as frequent as gamma-rays, but observed much less frequently due to observational limitations. The INTEGRAL satellite (see next section) is well-suited for the observation of hard X-ray afterglows. There are indications that such afterglows are present in the most luminous GRBs occurring about once in few months (2% of the sky observed by INTEGRAL). For instance, GRB120711A was seen by ISGRI and JEM-X for about 8 hours (**?**). The bright hard X-ray emission afterglow found to be related to the bright gamma-ray afterglow, observed by Fermi/LAT in the energy range above 100 MeV with a consistent power-law spectrum with index -2.

In this study, we assume that every BNS merger produces a hard X-ray afterglow with a spectrum similar to GRB120711A, but rescaled to the total EM luminosity of a typical short GRB - 10^{50} erg^{-2} s^{-1}. We extrapolate this spectrum to the off-axis case using Model I in (**?**).

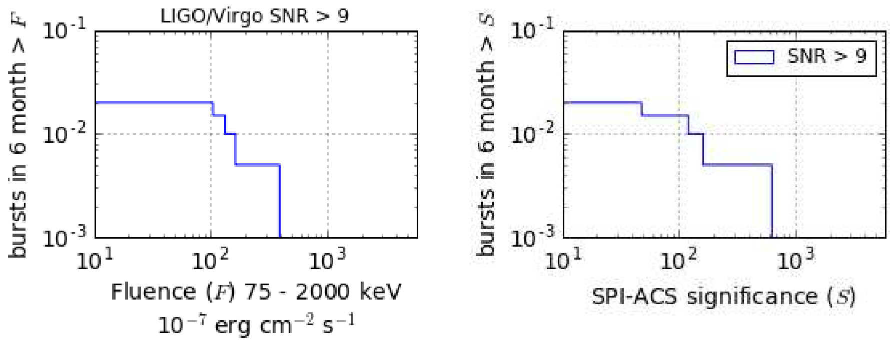

Figure 1. (*Left*) Cumulative distribution of the detected fluences by INTEGRAL in the LIGO/Virgo O2 run.(*Right*) Cumulative distribution of the significance in the INTEGRAL/SPI-ACS instrument.

The INTEGRAL mission and possible follow-up strategies

The INTEGRAL satellite (**?**) carries a combination of pointing instruments (IBIS which includes ISGRI, JEM-X, OMC and SPI), covering wide energy range from 3 keV to 10 MeV with a field of view up to 900 deg^2. SPI and IBIS are associated with SPI-ACS and IBIS-Veto that are shields made of BGO scintillator with sufficiently collecting area that they can be considered as instruments in their own right. This allows a *passive* follow-up using the near all-sky instruments SPI-ACS and IBIS-Veto and an *active* follow-up where the satellite is repointed. In this study, we assume that every GW alerts is followed actively. Typical latency of INTEGRAL observations is about 1 day but may be lower in some circumstances. We compute the flux at several moments of time, and compare it with ISGRI sensitivity in 100 ks exposure.

Results

Prompt – Passive follow-up

Choosing an isotropic sky distribution for the passive follow-up emission (passive follow-up) of our GW events, we show that in every case where the Earth is within the GRB emission cone, INTEGRAL detects prompt emission with significance at least 50 sigma. The rate of detection is 0.02 in the 6 months of O2 for GW alerts (SNR $\geq$ 9). Using SPI-ACS, IBIS/Veto, and IBIS it is possible to derive crude localization of these events. The accuracy of this localization strongly depends on the true source location, and ranges from 10% to about 50% of the sky.

Afterglow – Instrument repointing

If we want to follow-up the afterglow emission, we will need to re-point the on-board instruments. INTEGRAL can point only to a fraction of the GW localization region. For each event we compute the total localization probability within the observable region, and find that in 40% of the cases 80% of the localization is observed. However, if the complete available region is followed up every time, in total 80% of the true source locations are covered.

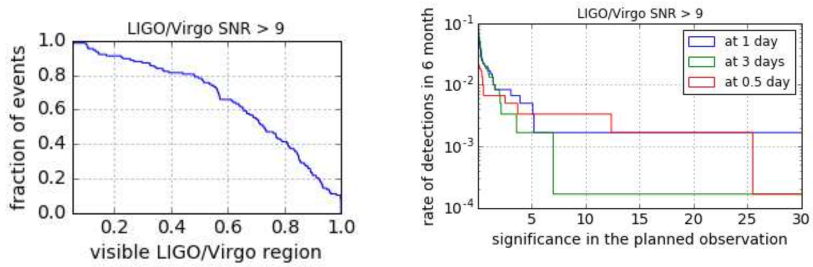

Figure 2. (*Left*) Cumulative distribution of the fraction of the LIGO/Virgo localization region accessible to INTEGRAL pointed follow-up observation in the LIGO/Virgo O2 run. (*Right*) Significance distribution on detected sources depending on time delay after the prompt emission.

With the assumptions We find that the expected rate of 5 sigma detections is only about 0.001 events in 6 months of O2. However, the rate of detections is very sensitive to the GRB energetics. We therefore focus on another possibility, that 10% of the events launch much more energetic outflow, in agreement with luminosities observed in real short GRBs. In this case we expect about 0.01 events seen in 6 months.

We stress that the afterglow prediction is particularly sensitive to assumptions on rather uncertain source model, and we assume only one, yet realistic, option.

IBIS/ISGRI achieves sensitivity of 3.7×10^{-11} erg cm^2 s in 20-60 keV in an area of about 1000 deg^2, with a continous 100 ks exposure, reaching deeper than any other hard X-ray telescope in such an extended sky region. It make INTEGRAL well-prepared to search for new and unexpected counterpars of the gravitational wave sources detected by LIGO/Virgo.

The temporal profile of the afterglow greately depends on the angle between the jet and the line of sight: light curves of the source observed at larger angles reach the maximum at a later moment. Assuming the jet is aligned with the binary rotation axis, the measurement of the inclination from the LIGO/Virgo data can be used to guide the follow-up observation. However, at the stages of LIGO and Virgo operations binary inclination is not measured with sufficient precision? **specify the precision, so I can compare to the dependencies**.

We can not reliably characterize the shape of the observed binary inclination distribution, limited by the simulation sample statistics. In our sample, equivalent to 200 times the projected LIGO O2 run, we identify 5 synthetic hard X-ray afterglow counterparts, among them 2 with off-axis angle larger than 10 degrees - the orphan afterglows.

What is the inclination distribution of the 40 % binaries whose GW error box can be covered to 80 % ? the same exactly, why would it be different? does the shape of the LIGO/Virgo localization region depend on the inclination?

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