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INTEGRAL results on the electromagnetic counterparts of gravitational waves

S. Mereghetti[1], V. Savchenko[2], C. Ferrigno[2], E. Kuulkers[3], P. Ubertini[4], A. Bazzano[4], E. Bozzo[2], S. Brandt[5], J. Chenevez[5], T. J.-L. Courvoisier[2], R. Diehl[6], L. Hanlon[7], A. von Kienlin[6], P. Laurent[8,9], F. Lebrun[9], A. Lutovinov[10,11], A. Martin-Carrillo[7], L. Natalucci[4], J. P. Roques[12], T. Siegert[6], and R. Sunyaev[10,13]

1 INAF, IASF-Milano, via E.Bassini 15, I-20133 Milano, Italy
2 ISDC, University of Geneva, chemin d'Écogia, 16 CH-1290 Versoix, Switzerland
3 ESA/ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
4 INAF, IAPS, Via Fosso del Cavaliere 100, 00133-Rome, Italy
5 DTU, Building 327, DK-2800 Kongens, Lyngby, Denmark
6 Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany
7 University College Dublin, Belfield, Dublin 4, Ireland
8 APC, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris Sorbonne Paris Cité, 10 rue Alice Domont et Léonie Duquet, 75205 Paris Cedex 13, France.
9 DSM/IRFU/SAp, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France
10 Space Research Institute, Profsoyuznaya 84/32, 117997 Moscow, Russia
11 Moscow Institute of Physics and Technology, Dolgoprudny, 141700, Russia
12 Université Toulouse, IRAP, 9 Av. Roche, BP 44346, F-31028 Toulouse, France
13 MPI for Astrophysics, Karl-Schwarzschild-Str. 1, Garching D-85741, Germany

Abstract. Thanks to its high orbit and a set of complementary detectors providing continuous coverage of the whole sky, the INTEGRAL satellite has unique capabilities for the identification and study of the electromagnetic radiation associated to gravitational waves signals and, more generally, for multi-messenger astrophysics. Here we briefly review the results obtained during the first two observing runs of the advanced LIGO/Virgo interferometers.

Key words. Gravitational waves – Gamma-ray bursts

1. Introduction

The INTEGRAL satellite, operating since 2002, is the main mission of the European Space Agency devoted to observations in the hard X-ray / soft γ-ray range with high spectral and angular resolution (Winkler et al. 2003). A few unique properties make it a particularly powerful tool in the context of multi-messenger astrophysics, that has recently entered an exciting phase (van den Heuvel 2017), thanks to the high sensitivity reached by the LIGO/Virgo interferometers for gravitational waves (GW) and by the new generation of neutrino detetectors.

The instruments on board INTEGRAL, besides providing high sensitivity with good imaging and spectroscopic capabilities over a wide field of view (~900 deg^2), are able to detect transient γ-ray signals from every direction in the sky, as discussed in more detail in section 2.

The other crucial property of INTEGRAL in this context is its highly eccentric orbit, with a period of 2.7 days. This allows uninterrupted observations of virtually the whole sky for 85% of the time (i.e. when the satellite is above the van Allen radiation belts). Note that, contrary to what happens for satellites in low earth orbits, the fraction of the sky occulted by the Earth is negligible (from 0.05% at perigee to a maximum of ~0.4% when INTEGRAL is close to the radiation belts). In addition, all the data are continuously transmitted to ground in real time and can be processed at the INTEGRAL Science Data Center (Courvoisier et al. 2003), with a latency of only a few seconds from the time of their on-board acquisition (Mereghetti et al. 2003).

In the next sections we describe the performance of the INTEGRAL instruments and review the results obtained during the O1 (September 2015 – January 2016) and O2 (December 2016 – August 2017) observing runs of the LIGO/Virgo detectors.

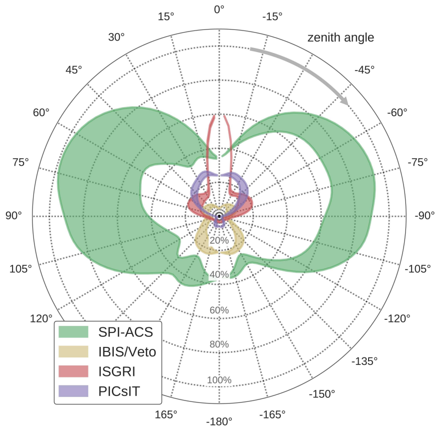

Fig. 1. Relative sensitivity of the different detectors on board INTEGRAL as a function of the photon arrival direction (Savchenko et al. 2017c). The shaded regions indicate the variation in sensitivity in the different azimuthal directions. A burst with duration of 1 s and Comptonized spectrum with $\alpha = -0.5$ and $E_p = 600$ keV has been assumed.

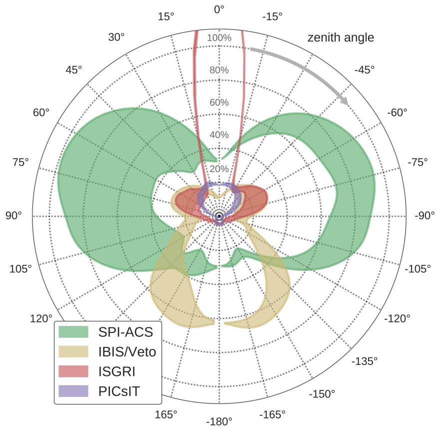

Fig. 2. Same as Fig. 1 but for a burst with duration of 8 s and a Band spectrum with $\alpha = -1$, $\beta = -2.4$ and $E_p = 300$ keV. Note that in this case the IBIS/VETO provides a better sensitivity than the SPI/ACS for events coming from the bottom direction.

2. INTEGRAL performances

The INTEGRAL satellite carries two main instruments, SPI and IBIS, operating at hard X-ray / soft γ-ray energies, complemented by an X-ray and an optical telescope (JEM-X and OMC). All these instruments observe simultaneously and point in the same direction. IBIS uses two position-sensitive detectors (ISGRI and PICsIt) coupled to a coded mask to provide images in the range from 20 keV to 10 MeV over a field of view of $\sim 30° \times 30°$ with an angular resolution of 12 arcmin (Ubertini et al. 2003). A similar field of view and energy range are covered by SPI. Its angular resolution is worse than that of IBIS, but thanks to its germanium detectors, SPI provides an excellent spectral resolution which makes it particularly useful to search for narrow lines from electron-positron annihilation or nuclear deexcitation (Vedrenne et al. 2003).

Both the IBIS and SPI telescopes include active anticoincidence systems, based on BGO scintillators, that can be used very effectively as omnidirectional detectors capable to monitor the entire sky. Due to their different geometry and to the presence of surrounding absorbing material, the response of these detectors is a significant (and energy-dependent) function of the arrival direction of the photons (see Fig. 1 and 2). The highest sensitivity is given by the SPI anticoincidence shield (SPI/ACS), which is sensitive to photons of energy above ~75 keV and provides light curves with fixed binning of 50 ms of the total count rate of the whole detector. The IBIS/Veto is sensitive in the 100 keV - 10 MeV range and provides light curves with a time resolution of 8 s. Due to the lack of spectral and directional information of these detectors, whose main purpose is to shield the focal planes of the respective telescopes, it is necessary to assume a spectral shape and sky position to convert their measured count rates to photon fluxes in physical units.

Finally, we note that, due to the high penetrating nature of γ-rays, both ISGRI and PICsIt are sensitive also to events coming from sky regions outiside the imaging field of view. From a comparison of the relative number of counts revealed in all the different elements that constitute the INTEGRAL payload it is possible to derive some rough information on the sky location of transient events.

A more complete description of the performances of the INTEGRAL instruments for the search of GW counterparts and other transient events can be found in Savchenko et al. (2017c).

3. Results

3.1. GW 150914

The first gravitational wave signal significantly detected during the O1 run of the Advanced LIGO interferometer, GW 150914, was located inside an uncertainty region (90% confidence) with area of 630 deg^2 (Abbott et al. 2016b). At the time of the GW trigger, INTEGRAL was pointing away from the GW error region, but its orientation was optimal to cover the whole uncertainty region with the SPI/ACS. Indeed in 95% of the error region the achieved sensitivity was within 20% of the best value, providing constraining upper limits on the fluence above 75 keV of possible counterparts (Savchenko et al. 2016). These limits depend on the assumed duration Δt of the event, and to a lesser extent, on its sky position and spectral shape. For typical GRB spectra, the 3σ upper limits range from 2×10^{-8} erg cm^{-2} (Δt=50 ms) to $\sim 10^{-6}$ erg cm^{-2} (Δt=10 s).

A possible hard X-ray transient lasting ~1 s was detected with the Fermi/GBM instrument about 0.4 s after the GW trigger time (Connaughton et al. 2016). The significance of this event and its association to the GW source are subject of discussion (Greiner et al. 2016; Connaughton et al. 2018). If confirmed, this would be a rather surprising result since GW 150914 was caused by the coalescence of two black holes (Abbott et al. 2016a) and most models do not predict electromagnetic emission in this case.

A comparison of the Fermi/GBM results with the INTEGRAL upper limits is not straightforward, owing to the poorly constrained spectrum and uncertain arrival direction of this weak event. The GBM response extends to lower energies than that of the SPI/ACS and, in principle, the results of the two instruments could be reconciled if the putative counterpart of GW 150914 had a very soft spectral shape, different from that of the majority of GRBs. On the other hand, the GBM data favor a relatively hard spectrum (e.g. a Comptonized model with $\alpha_{comp} = -0.42$ and $E_{peak} > 1$ MeV; Veres et al. 2016) that would result in a significant signal in the SPI/ACS. Further work, also to investigate the relative intercalibration of the two instruments, is required to give a better assessment of the properties of this electromagnetic signal and its possible association to GW 150914.

3.2. GW 151226

At the time of this event, produced by the coalescence of two black holes (Abbott et al. 2016c), INTEGRAL was not observing be-

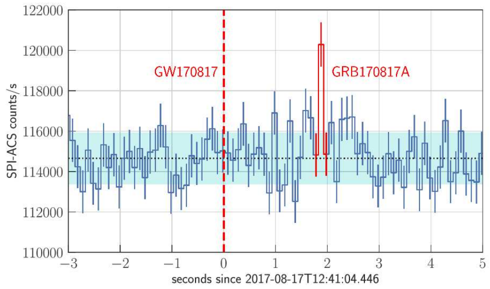

Fig. 3. SPI/ACS light curve around the time of GW 170817, binned at 100 ms (from Savchenko et al. 2017a). The vertical dashed line indicates the time of the GW trigger.

cause it was close to the perigee, below the Earth radiation belts.

3.3. GW 170104

GW 170104 was the first high-significance event revealed during the LIGO O2 observing run. Also this signal was caused by the merging of two black holes (Abbott et al. 2017a). It was localized within an uncertainty region (90% confidence) of ~1200 deg^2. This region was entirely visible with good sensitivity by the SPI/ACS, but no significant signals were detected (Savchenko et al. 2017a). The derived upper limits are similar to those obtained for GW 150914. For example, assuming a typical spectrum for a short GRB (a cutoff power-law with $\alpha = -0.5$ and $E_p = 600$ keV) the SPI/ACS 3σ upper limit for the 75-2000 keV fluence in a duration of 1 s is below $2{\times}10^{-7}$ erg cm^{-2} in 95% of the LIGO localization region.

Verrecchia et al. (2017) reported the possible detection of a weak and short (32 ms) burst, occurring 0.46 s before the GW trigger time, in the data of the MCAL detector on the AGILE satellite. For most of the localization region of GW 170104 the SPI/ACS provides an upper limit inconsistent with the fluence estimated with the AGILE/MCAL.

3.4. GW 170814

GW 170814 was the first event revealed by three gravitational waves interferometers. Thanks to the inclusion of the Virgo data it was possible to derive a small localization region of only 60 deg^2 (Abbott et al. 2017b). Also in this case, no significant signals were found with the SPI/ACS at or near the time of the GW trigger (Savchenko et al. 2017b).

An INTEGRAL follow-up observation started about two days after the GW trigger and covered more than 90% of the localization region in the imaging field of view of IBIS and SPI with a maximum net exposure of ~100 ks. No counterparts were found, with a 3σ upper limit on the average flux of ~3 mCrab (13 mCrab) in the 20–80 keV (80–300 keV) energy range (Savchenko et al. 2017e).

3.5. GW 170817

The first gravitational wave signal produced by the merger of two neutron stars was revealed by the the LIGO/Virgo interferometers on August 17, 2017 (Abbott et al. 2017c), while INTEGRAL was pointing toward the localization region of the previous event, GW 170814. The independent discovery by the Fermi/GBM (Goldstein et al. 2017) and by the SPI/ACS (Savchenko et al. 2017d) of an electromagnetic signal clearly associated to GW 170817 is a milestone of multi-messenger astrophysics. This event has important physical and astrophysical implications on many phenomena, such as, e.g., the speed of gravitational waves, the Lorentz invariance, the equivalence principle, the equation of state of neutron stars and the physics of GRBs (Abbott et al. 2017d).

The SPI/ACS light curve around the time of GW 170817 is shown in Fig. 3. The excess corresponding to GRB 170817 is detected with a signal to noise ratio of 4.6, 1.9 s after the GW trigger time, As expected for such a faint γ-ray burst, no coincident signal was visible in all the other INTEGRAL detectors, thus supporting that the excess seen in the SPI/ACS was not due to particle background. We derived a 75-2000 keV fluence of $(1.4 \pm 0.4 \pm 0.6) \times 10^{-7}$

erg cm^{-2}, where the latter value gives the systematic error due to the uncertainty on the assumed spectral model.

INTEGRAL carried out a follow-up observation, initially centered at the best Fermi/GBM location of GRB 170817, and later repointed toward the optical counterpart, as soon as it was announced. This position was covered with a net exposure of more than 320 ks, starting about one day after the GW event, but no X-ray or γ-ray counterparts were detected. The 3σ upper limits on a long-lasting afterglow are of the order of ~1–10 mCrab for energies below ~100 keV and of few hundreds of mCrab in the MeV region.

Finally, thanks to the long INTEGRAL follow-up observation, we could also search for delayed bursting activity, as could be expected if (at least temporarily) a magnetar is formed, and for the presence γ-ray lines from r-process elements, such as I or Cs. In both cases the results were negative, and no other mission could provide limits better than those obtained with the INTEGRAL instruments.

4. Conclusions

About fifteen years after its launch, INTEGRAL has started a new exciting phase of its scientific life by playing a major role in the era of multi-messenger astrophysics. In the case of black hole binary mergers, it has provided unique upper limits that constrain the ratio of emitted electromagnetic to gravitational energy to values $E_{\gamma}/E_{GW} \lesssim 10^{-7} - 10^{-5}$. In the case of the first, and up to now single, GW event produced by the coalescence of two neutron stars, INTEGRAL has given a crucial independent confirmation of the short GRB discovered by Fermi/GBM, as well as important upper limits on subsequent high-energy emission on different timescales.

The unique INTEGRAL performances discussed above are relevant also in the search for counterparts of astrophysical neutrinos, as demonstrated in several recent cases for which constraining upper limits were provided (Savchenko et al. 2017f; Santander et al. 2017).

The THESEUS satellite (Amati et al. 2018), proposed for the ESA M5 call for new missions, is planned to be operative in the years following 2030, when GW astronomy will be a mature field, well beyond the current exploratory phase. The expected potentialities of THESEUS for multi-messenger astronomy are described in Stratta et al. (2018), but it is difficult to anticipate the wealth and variety of phenomena that THESEUS will address.

The lesson that can be learned from the INTEGRAL results described above, is that unanticipated uses of a payload can give important scientific contributions and exciting results. By definition, it is difficult to optimize the mission for an unforeseen science exploitation, but some general guidelines can be followed, as including the possibility of reconfiguration of the on-board software (with the associated problem of mantaining the required expertise for an extended time period). Also important are an accurate calibration of all the active elements (including unconventional directions and energies), as well as a complete characterization of both payload and spacecraft with an accurate mass model.

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