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INTEGRAL Observations of Gravitational Waves Events from the Ongoing O4 Run

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Since the beginning of the gravitational wave (GW) astronomy era in 2015, telescopes across the electromagnetic (EM) spectrum began to search for counterparts of GW events. The first, and so far only, EM counterpart (GW170817/GRB170817A) revealed a plethora of information from both the prompt and the afterglow emission relevant to fundamental physics and astronomy. However, the event yielded a host of questions, many of which require additional events to answer. The detection of the prompt emission is critical as it provides information about the energetics of the event, constraints on fundamental physics, and better localization for follow-up observations at other wavelengths. The *INTEGRAL* satellite, with its large field-of-view and broad coverage in the X-ray to soft gamma-ray energy range, is well-suited to detect, localize, and follow-up GW triggers during the current LIGO/Virgo/KAGRA observing run, O4. We discuss the *INTEGRAL* detectors, analyses, and the results from the current O4 observing run.

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1. Introduction

The detection of the binary black hole (BBH) merger GW150914 by LIGO [1] began the era of gravitational wave (GW) astronomy. The first three observing runs by LIGO/Virgo, beginning in 2015, revealed a previously unknown population of high-mass BHs [2]. To date, no electromagnetic (EM) counterparts have been detected for any BBM mergers. Thus they are likely not EM sources, except in high-density environments (See for example [3]).

The lone GW event with a EM counterpart was the binary neutron star (BNS) merger GW 170817. Its prompt emission counterpart was the short gamma-ray burst GRB 170817A, and its afterglow AT2017gfo. This event has produced a wealth of results for fundamental physics and across the EM spectrum. The time difference between the GW trigger and the prompt EM trigger ($\sim$ 1.7 s after) was used to investigate fundamental physics by attempting to determine the speed of gravity, test Lorentz variation limits, the equivalence principle, and also constrain the neutron star equation of state [4].

The event confirmed that at least some short GRBs are due to BNS mergers. Also, the GRB has an unusually low luminosity [5], which was interpreted as viewing a structured jet off-axis. Subsequent observations at soft X-ray and radio wavelengths have supported that interpretation [6]. The shape of GRB jets is a longstanding question thus this event has provided some insight.

A remaining open question about BNS mergers/short GRBs is the remnant of the event. Multiple scenarios have been proposed: the formation of a BH directly, a stable neutron star (NS), or a massive neutron star that lasts from ms to hours before becoming a BH [7]. The earliest pointed observations of the source were performed by *INTEGRAL* roughly 19.5 hours after the trigger [8]. Therefore it was not able to investigate the possibility of a short-lived NS.

As the fourth observing run begins (O4), a host of questions persist, and detections of prompt emission at hard X-rays/soft gamma-rays are important as they are critical to understanding the merger energetics and better localizing the event to enable follow-up observations across the EM spectrum. The *INTEGRAL* satellite's characteristics enable it to detect the prompt emission and quickly perform follow-up obervations from X-rays to gamma-rays to study the afterglow emission and the merger remnant.

2. The *INTEGRAL* Satellite

The *INTErnational Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*) was launched in Oct 2002 from Baikonur, Kazakhstan with an eccentric orbit of $\sim$ 3 days [9]. This highly elliptical orbit enables long-uninterrupted observations of nearly the entire sky for more than 85% of an orbit. *INTEGRAL*'s suite of instruments cover 3 keV to 14 MeV with a range of fields-of-view (FoVs) from ~100's −1000's deg2 [10]. Thus its pointed instruments (JEM-X (3-30 keV, [11]), IBIS (18 keV − 14 MeV, [12]), and SPI (20 − 8000 keV, [13]) are well-suited for serendipitous observations of impulsive events.

2.1 IBAS

INTEGRAL does not have any onboard triggering capabilities, but the data are continuously telemetered to ground, which allows for rapid searches of impulsive events. The INTEGRAL Burst

Alert System (IBAS) [18] was developed to quickly analyze the data from the IBIS- Imager on Board the INTEGRAL Satellite (ISGRI) and the SPI-Anticoincidnce System (ACS). GRBs detected within the ISGRI FoV occur roughly 1/month and can be localized to approximately 3 arcmin. SPI-ACS GRB detections occur ∼ 1/day, but with no position information.

2.2 SPI-ACS

SPI-ACS is perpendicular to the *INTEGRAL* pointing direction. It was not designed as a GRB detector, but its large effective area (0.7 m^2) in the 75 – 2000 keV energy range and time resolution of 50 ms was known to be a sensitive GRB monitor since the launch of the mission [14].

2.3 IBIS-VETO

The IBIS-VETO covers the sides and bottom of the IBIS detector planes [15, 16]. It has a time resolution of 8 s. It can detect impulsive events, though with no localization capabilities.

2.4 IBIS-PICsIT

The IBIS soft gamma-ray detector, PICsIT, covers the ∼ 200 kev −14 MeV energy range. The spectral-timing data have a time resolution of 3.9-ms, but no position resolution. Also, its energy range is 200 – 2600 keV in 8 energy channels. See Figure A.1 in [16] for a diagram on the angular dependence sensitivity of each detector.

3. Search for EM Counterparts with *INTEGRAL*

LIGO/Virgo/KAGRA GW triggers are distributed to the community via NASA's Gamma-ray Coordinates Network (GCN) Circulars. After receiving an alert, software pipelines automatically analyze the data from the different *INTEGRAL* detectors to search for impulsive events close in time (±300 s) to the reported trigger time. The analyses of the different detectors occur in real-time or near real-time, depending on the availability of the data. The light curves and results from the analyses are shown on an online platform page, which shows the results from the various detectors along with the *INTEGRAL* visibility of the sky and the GW trigger localization. The SPI-ACS analysis also calculates the fluence (or the $3-\sigma$ upper limit) in the 75 – 2000 keV energy range based on the position of the GW event. The analysis calculates fluences (or upper limits) in two scenarios: a long GRB Band model ($\alpha = -1, \beta = -2.5, E_{peak}$ = 300 keV lasting 8 s) and a short GRB cutoff power-law model ($\Gamma = -0.5, E_{peak}$ = 500 keV lasting 1 s), as done in [8, 16].

After the analyses have finished, a brief GCN circular is automatically written that includes the results from the fluence or upper limit calculations and list of SPI-ACS excesses with their signal-to-noise ratio, flux, and false alarm probability. This process is sent out to the community by a burst advocate. The multi-detector analyses can often be completed in a few hours, depending on how quickly the data are available. This process has been active since the beginning of O3 and has continued during O4. In the case of a detection and the event is moderately well-localized, the burst advocate can request Target of Opportunity (ToO) observations.

Table 1 lists the trigger name and the SPI-ACS upper limit for all GW triggers from LIGO/Virgo with *INTEGRAL* observations through O3. *INTEGRAL* instruments are not operational during

Table 1: EM Upper Limits from SPI-ACS Prior to O4

Name	Upper Limit (erg/cm^2)	Name	Upper Limit (erg/cm^2)	Name	Upper Limit (erg/cm^2)	Name	Upper Limit (erg/cm^2)
S190521r	4×10^{-7}	S190923y	3.4×10^{-7}	S200213t	4.8×10^{-7}	S200316bj	4.3×10^{-7}
S190521g	1.7×10^{-7}	S190915ak	2×10^{-7}	S200208q	2.3×10^{-7}	S200311bg	4.5×10^{-7}
S190521r	4×10^{-7}	S190910h	3.1×10^{-7}	S200129m	4.5×10^{-7}	S200302c	3.2×10^{-7}
S190519bj	2.9×10^{-7}	S190910d	2.2×10^{-7}	S200128d	2.6×10^{-7}	S200225q	2.1×10^{-7}
S190517h	2.7×10^{-7}	S190901ap	1.7×10^{-7}	S200114f	3.1×10^{-7}	S200224ca	3×10^{-7}
S190513bm	2.6×10^{-7}	S190828l	1.8×10^{-7}	S200105ae	2.2×10^{-7}	S200219ac	2.4×10^{-7}
S190503bf	2.4×10^{-7}	S190828j	2×10^{-7}	S191215w	3.3×10^{-7}	S200213t	4.8×10^{-7}
S190426c	1.74×10^{-7}	S190814bv	3.1×10^{-7}	S191213g	5.2×10^{-7}	S200208q	2.3×10^{-7}
S190425z	2×10^{-7}	S190728q	2.6×10^{-7}	S191205ah	1.8×10^{-7}	S200129m	4.5×10^{-7}
S190421ar	1.9×10^{-7}	S190727h	2.1×10^{-7}	S191204r	3.4×10^{-7}	S200128d	2.6×10^{-7}
S190412m	2.9×10^{-7}	S190720a	1.8×10^{-7}	S191110af	5×10^{-7}	S200114f	3.1×10^{-7}
S190408an	2.5×10^{-7}	S190718y	2.8×10^{-7}	S191110af	2.8×10^{-7}	S200316bj	4.3×10^{-7}
G299232	3.6×10^{-7}	S190707q	2.6×10^{-7}	S191109d	5.3×10^{-7}	S200311bg	4.5×10^{-7}
G298389	4×10^{-7}	S190706ai	1.7×10^{-7}	S191105e	2.3×10^{-7}	S200302c	3.2×10^{-7}
G297595	2.1×10^{-7}	S190701ah	1.6×10^{-7}	S190930t	3.3×10^{-7}	S200225q	2.1×10^{-7}
G288732	4.3×10^{-7}	S190630ag	1.9×10^{-7}	S190930s	1.8×10^{-7}	S200224ca	3×10^{-7}
G284239	1.5×10^{-7}	S190602aq	3.8×10^{-7}	S190924h	4.2×10^{-7}	S200219ac	2.4×10^{-7}

periods when the satellite is close to the Earth's radiation belts to limit damage to the instruments, roughly 15% of the orbit. Thus some of the GW triggers when *INTEGRAL* was not operational and do not have observations. Therefore these events were not included in Table 1. See [17] for a more detailed list.

4. *INTEGRAL* O4 Results

As part of O4, the SPI-ACS data have been made available to the InterPlanetary Network (IPN)[1] with $\sim$ 20 s lag for triangulation of any EM counterparts with instruments such as *Fermi*/GBM, *Swift*/BAT, Konus-Wind, and others. These localization regions then can be sent to the community for follow-up observations at other wavelengths. This process is already incorporated for GRB localization. Also, alerts with times and false alarm probabilities for excesses above the background are sent out via the HERMES platform. If the merger contains a NS, a fluence upper limit is submitted via a GCN Circular. So far the upper limit fluences range from $1.8 - 3.8 \times 10^{-7}$ erg/cm^2.

Table 2 includes the reported upper limits from SPI-ACS for the GW triggers from the current O4 observing run, which is on-going until the end of 2024. So far no EM counterparts have been reported for any LIGO/Virgo/KAGRA events during O4.

5. Conclusion

[1]https://www.fe.infn.it/~guidorzi/doktorthese/node23.html

The analysis of the *INTEGRAL* Multi-Messenger analysis pipeline, which automatically looks for EM counterparts to reported GW triggers, is operational during the current LIGO/Virgo/KAGRA O4 run. As part of the pipeline, a fluence or upper limit is calculated from the SPI-ACS data, which can be sent to the community via GCN. Due to the numerous BBHs without an EM counterpart, SPI-ACS notices are currently sent only for events including a NS. So far SPI-ACS upper limits have been reported for three events ($\sim 1.8 - 3.8 \times 10^{-7}$ erg/cm^2) and no significant detections. For BBH events, alerts with times and false alarm probabilities for excesses above the background are sent out via the HERMES platform.

Table 2: EM Counterpart Search from SPI-ACS for O4

Name	Upper Limit (erg/cm^{-2})
S230527c	1.8×10^{-7}
S230529ay	3.4×10^{-7}
S230518h	3.8×10^{-7}

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