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Hunting for elusive multi-messenger transients with INTEGRAL

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Abstract. Recent years were marked by breakthrough observations of new multi-messenger and multi-wavelength transients, often unveiling unanticipated and puzzling phenomena. Likely associated with most energetic processes in the dense region at the heart of the peculiar supernovae, mergers of compact objects, or tidal disruption events, these events expose unique signatures in hard X-ray and gamma-ray emission.
I will highlight recent pioneering observations of short energetic transients made with INTEGRAL, which is especially well-equipped to observe unpredictable, short-lived, and energetic hard X-ray and gamma-ray transients. INTEGRAL carries a collection of detectors that monitor the entire hard X-ray sky with over 80% duty cycle and are able to re-point on a relatively short time scale to perform deep and sensitive hard X-ray observations of a large selected sky region. I discuss the observations of gamma-ray bursts, in particular in association with the gravitational wave events and high-energy neutrinos, and review how INTEGRAL observations of fast hard X-ray transients help to reveal mechanisms of peculiar supernovae. Finally, I will discuss how the recent discoveries in the domain of multi-messenger transients were made possible by a global effort to achieve a new degree of automation and interoperability.

1. Introduction

Recently emergence of rapid optical and radio surveys accelerated development of time domain astronomy. Furthermore, observations of gravitational waves and neutrinos enabled breakthrough multi-messenger observations of fundamental physical processes in space. Short and energetic events are generally easier to separate from the background than persistent sources, and this is why the first truly multi-messenger signals were also detected as transient events.

The properties or even the nature of these new transient sources often remain uncertain, but it appears as they are typically associated with peculiar supernovae, mergers of compact objects, or tidal disruption events. An important perspective on these events is given by hard X-ray and gamma-ray emission: it tends to reveal a distinct emission component that points to the most dense and energetic regions at the heart of the source.

In this paper we highlight recent pioneering observations of short energetic transients made with INTEGRAL, which is especially well-equipped to observe unpredictable, short-lived, and energetic hard X-ray and gamma-ray transients. It carries a collection of detectors that monitor the entire hard X-ray sky with over 80% duty cycle and are able to re-point to perform deep and sensitive hard X-ray observations of a large selected sky region.

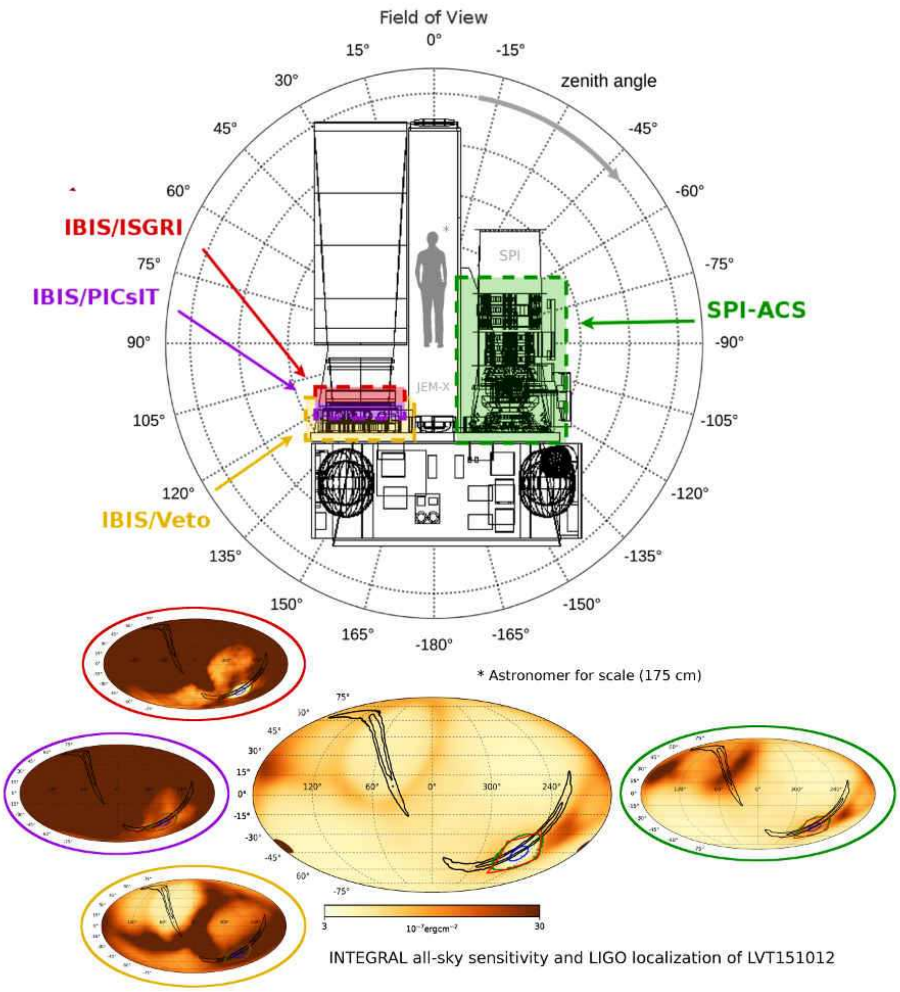

Fig. 1. Schematic view of the INTEGRAL spacecraft, highlighting the all-sky instruments. A typical astronomer is shown for scale inside JEM-X monitor. The bottom panel shows contribution to the all-sky sensitivity to any gamma-ray counterpart from GW151012 from different all-sky detectors on-board INTEGRAL (note the color coding matching the top panel), (see Savchenko et al. 2017, for detailed study)

2. INTEGRAL observatory

INternational Gamma-Ray Astrophysics Laboratory (INTEGRAL Winkler et al. 2003) is an M-class ESA mission, operating since 2002 - 2029. It is equipped to study hard X-ray and gamma-ray emission in the energy range from 3 keV to more than 10 MeV.

Photons in this energy range are typically produced in dense and energetic regions by non-thermal particles, through synchrotron radiation, compton scattering, nuclear decays, etc. Due to particularily low cross-section, this emission can reach to the deepest regions in the vicinity of the compact sources, undergoing relativistic transformations. On the other hand, photons with these energies are also particularily hard to intercept and characterize. INTEGRAL relies on a collection of very heavy detectors, with large stopping

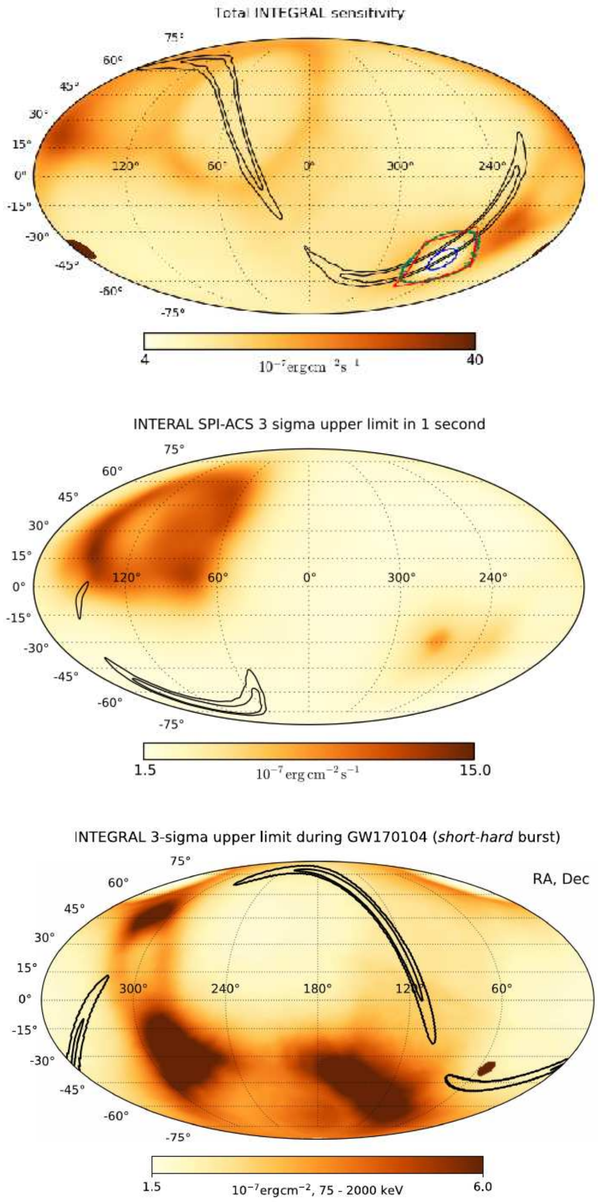

Fig. 2. INTEGRAL upper limits on gamma-ray counterpart of several BBH mergers found by LIGO in realtime durting O1 and O2 (Savchenko et al. 2017; Savchenko et al. 2017a; Greiner et al. 2016; Savchenko et al. 2016)

power. A set of coding masks, projecting throughly designed patterns on the detectors, maximizing the capacity to distinguish different sources in the intricate superposition of different shadows. The coded masks are only projected within limited Fields of View (within 1000 deg^2), but due to exceptional penetrating power of photons above 100 keV,

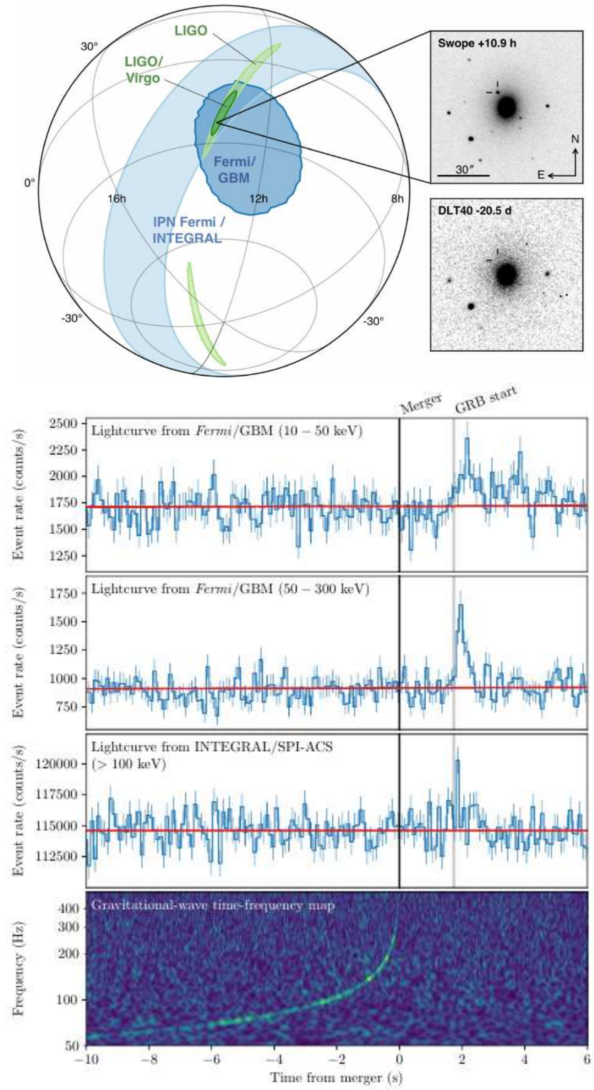

Fig. 3. INTEGRAL and Fermi observation of GRB170817A, coincident with GW170817 (Abbott et al. 2017; Goldstein et al. 2017; Savchenko et al. 2017b)

they reach the same detectors from any direction in the sky. Sometimes a nuissance, they also imply that INTEGRAL has exceptional grasp for hard X-ray emission from any position in the sky, especially important when the sources appear unexpectedly at random sky positions, preventing any scheduled observations with narrow-field instruments. Since multiple INTEGRAL instruments can be used in this fashion, it is possible to reconstruct sky direction by studying relative properties of the signal in different observables (Savchenko et al. 2017).

Furthermore, owing to its highly elongated orbit, INTEGRAL does not experience any Earth occultation, unlike any low-orbit spacecraft (like Fermi, AGILE, or Swift). INTEGRAL instruments are online 85% of the

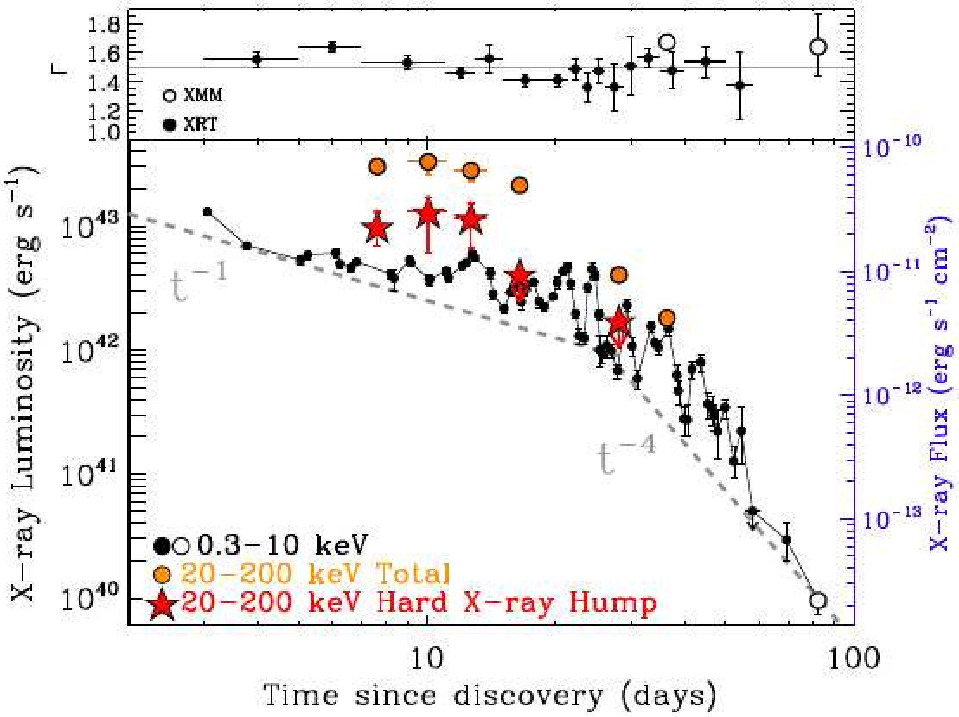

Fig. 4. INTEGRAL, Swift, and NuSTAR observations of AT2018cow (Ferrigno et al. 2018; Savchenko et al. 2018; Margutti et al. 2018)

time, just to give a sufficient margin to avoid the damaging the instruments in the radiation belts.

3. Observations of GW transients

Since 2015, LIGO detector network has been making ground-breaking observations of gravitation wave bursts, later joined by also by Virgo. The most clear GW signal events is emitted in short bursts just before coalescence of compact binary objects, such as black holes and neutron stars. It is not currently possible to pinpoint the distant compact binary before its collapse, and the localization provided by the GW network is still rather uncertain. This implies that the best observations close to the time of the events come from detectors which do not need to be pointed to a particular source, observing the whole sky at once. As described in the previous section, INTEGRAL, fits extremely well to these requirements. From the very first GW detection, INTEGRAL has been performing unique and vital observations of the first GW transients - binary Black Hole mergers. No gamma-ray signal was found by INTEGRAL from any of the BBH mergers (Savchenko et al. 2017; Savchenko et al. 2017a; Greiner et al. 2016; Savchenko et al. 2016) (see Fig. 2). A report of a low-significance gamma-ray counterpart of GW150914 by Fermi/GBM(Connaughton et al. 2016; Greiner et al. 2016; Xiong 2016; Lyutikov 2016) sparked considerable interest in a possibility that such counterparts might exist, despite any expections. Implications of the INTEGRAL upper limits on the Fermi/GBM observations remain uncertain, owing to challenges in characterizing and comparing such a low-significance event between two instruments with only partially overlapping energy ranges and considerably differenct strong sides.

The capacity of INTEGRAL to detect gamma-ray counterparts of the GW sources was inevitably demostrated by the detection of the first GRB associaed with a GW burst, GRB170817A Fig. 3. Owing to its superiour sensitivity and nearly uninterrupted observations, INTEGRAL was essentially guaranteed to observe it, while even Fermi/GBM, although being more sensitive that SPI-ACS to softer events, almost missed it due to the SAA passage (contributing to its 50% duty cycle).

First detection of GRB-GW source exceeded all but most optimistic expectations: short GRBs were only known to occur at relatively large distances, well outside LIGO/Virgo reach GRB170817A was instead a very nearby, very sub-luminous event. It did not quite fit in the basic GRB framework, and required extensions involving low-power wide-angle outflow, such as part of the stuctured jet, a cocoon inflated by provpagation a "normal" ultra-relativistic GRB jet (Lazzati et al. 2017; Gottlieb et al. 2017; Lazzati & Perna 2019; Fraija et al. 2019), or even delayed activity of a long-living remant of the merger - likely a young magnetar (Gao & Fan 2005; Kashiyama et al. 2015; Margalit et al. 2018).

4. INTEGRAL detection of Hard X-ray component in AT2018cow

Although the pivital role of INTEGRAL in observations of short impulsive gamma-ray transients has been firmly established, the searches of slowly decaying weak hard X-ray sources with its pointed coded mask instrument were always seen rather more in an explorative perspective. Until recently, no stellar-scale object has been detected from distances at which any GRB or GW sources are found. This has changed last year, when a coordinated real-time effort enabled the detection of AT2018cow, likely an exceptionally fast and luminous supernovae at 60 Mpc (Prentice et al. 2018; Ferrigno et al. 2018; Savchenko et al. 2018; Fang et al. 2018; Margutti et al. 2018; Kuin et al. 2018).

This means that INTEGRAL of fast hard X-ray transients now help to reveal mechanisms at the core of the some of short energetic transients likely associated with the deaths of the massive stars. Remarkably, the hard X-ray activity was likely drived by a young energetic object at the heart of the collapse, possibly similar to that discussed in the context of sGRBs and especially GRB170817A.

5. Conclusions

Recent progress highlighted role of Hard X-ray and soft gamma-ray emission in revealing inner workings of the multi-messenger relativistic sources. More more fruitful observations are being collected as multi-wavelength and multi-messenger observations are reaching new and puzzling kinds of sources. INTEGRAL features sufficient sensitivity to remain on the forefront of these synergystic studies for the years to come.

It is remarkable and important to note that recent discoveries in the domain of multi-messenger transients were made possible by a global effort to achieve a new degree of automation and interoperability, in which INTEGRAL is among the frontrunners, owing to the multiple synergystic efforts and developments maintained by Department of Astronomy at University of Geneva (in particular CDCI Neronov 2019; Savchenko 2019) as well as ESAC [1].

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