Electromagnetic counterparts to gravitational wave alerts

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Gravitational wave detection has begun a new era in astronomy. We can now observe mergers of compact objects, including neutron stars (NSs) and black holes (BHs) from a distant Universe and learn new things about the stellar evolution or formation of BHs. We review the current status of the electromagnetic observations of gravitational wave events with the involvement of the Polish astronomers. In particular, we describe the ESO's ENGRAVE Large Programme, which aims at prompt follow-up and study of counterparts for GW events.

1 Introduction

The era of multi-messenger astronomy started on 2017 August 17 then the merger of two NSs, dubbed GW170817, was detected in gravitational waves (GWs), electromagnetic (EM) radiation, ranging from γ-ray to radio, and neutrinos (Abbott et al., 2017b). Fortuitously, the event occurred in a relatively nearby galaxy NGC 4993 at just 48 Mpc, which made it possible to discover the EM counterpart. GW signal registered by LIGO interferometers was very strong and the lack of detection by Virgo helped constrain a very small ($\sim$22 square degree) sky localisation where the event came from. An almost simultaneous signal in γ-ray seen by the Fermi-LAT and INTEGRAL satellites confirmed the GW signal was related to a merger of NSs binary, called a kilonova, the idea first proposed by Li & Paczyński (1998). Counterpart in optical wavelengths was found just 11 hours later at $i = 17.5$ (AB) (Coulter et al., 2017), see Fig. 1. The first spectrum was taken a few minutes after the first image and was fairly blue (black body temperature around $\sim$11 000 K) and featureless (Shappee et al., 2017). Within the next few days the spectrum of the kilonova became significantly redder and showed a signature of the r-process enrichment (right panel in Fig. 1). In the UV range, the object disappeared after a week, in near-IR it was observed up to three weeks with the 8-m class telescopes (e.g. Smartt et al., 2017).

Radio jet was observed 200 days after the merger (Ghirlanda et al., 2019). This detection immediately provided answers to the questions of the origin of the short-duration gamma-ray bursts, as well as the synthesis of elements heavier than iron (e.g. Côté et al., 2017). In addition, a new route to measuring the Hubble constant (H_0) was established (e.g., Abbott et al., 2017a) and many alternative theories of gravity have already been discounted given the tight constraint on the difference between the speed of light and gravity. This discovery made also a strong impact on other fundamental issues, including dark matter (e.g., Bird et al. 2016), the equation of state of NSs, and the evolution of binary stars (e.g., Belczynski et al. 2016).

A significant role in most of these studies was played by the Polish scientists, from researchers involved in the POLGRAW collaboration, to those taking part

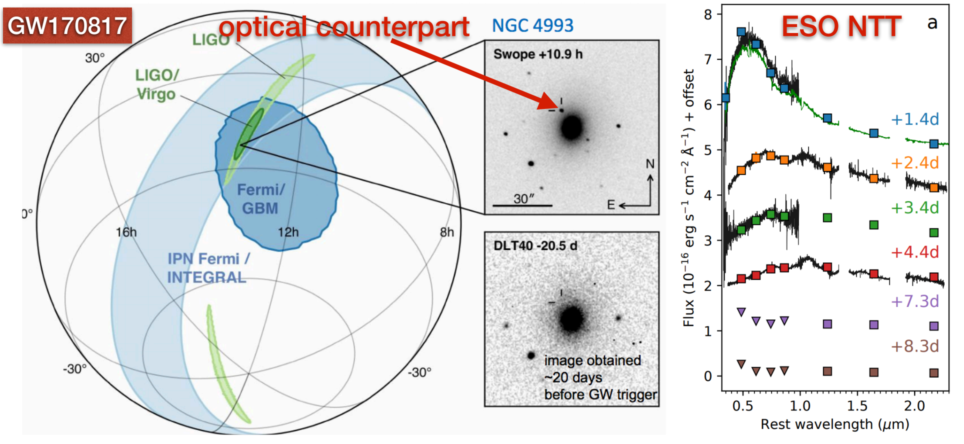

Fig. 1: GW170817, the first GW event with an electromagnetic counterpart detected. The left panel shows the sky localisation from LIGO and with Virgo constrains along with Fermi/Integral localisation of the gamma-ray signal. Insets show the discovery of the optical counterpart. The right panel shows the spectrum evolution of the kilonova as observed with ESO/NTT and ePESSTO group (figures compiled based on Smartt et al. 2017 with permission).

in the follow-up observations: Fermi-LAT (UJ), H.E.S.S. (CAMK, UW, IFJ, UJ, UMK), HAWC (IFJ), Pierre Auger (IFJ, UŁ, ESO/ePESSTO (UW) and Pi of the Sky (UW).

2 ENGRAVE

Successful follow-up observations and a very detailed study of GW170817 encouraged European astronomers to establish a large collaboration, which uses mostly ESO observing facilities to follow-up potential optical counterparts of Gravitational Wave events. The team was awarded a three-period large ESO programme to fully cover events detected during LIGO-Virgo's O3 Run in 2019-2020. Total awarded time was almost 180 hours in service mode, mostly including Target of Opportunity programme on X-Shooter, FORS2, HAWK-I, NACO, MUSE and nine hours as Rapid Response Mode on X-Shooter, HAWK-I and MUSE. Many members of the ENGRAVE collaboration are actively involved in counterpart searches including those using ESO facilities (e.g., VST, VISTA, NTT, GROND) and more widely (ATLAS, BlackGEM, GOTO, OGLE, Gaia, PanSTARRS and ZTF).

ENGRAVE is structured in nine working groups, each responsible for imaging, spectroscopy, polarimetry, radio/sub-millimetre techniques and other aspects like infrastructure, theory, etc. Every night and day when LIGO-Virgo interferometers are operating, there is a dedicated team of around 10 people on duty waiting for gravitational wave detection and potential counterparts identification, ready to trigger observation on ESO instruments and then reduce and analyse them in order to publish as soon as possible.

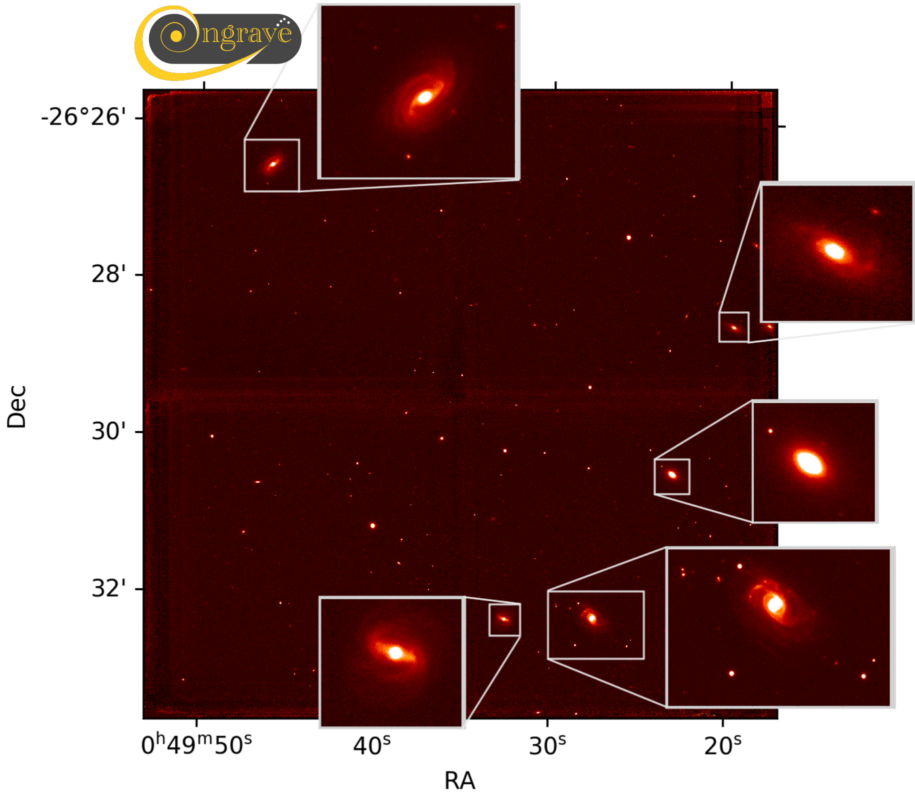

Fig. 2: S190814bv, Neutron Star-Black Hole (NS-BH) merger candidate was hunted for an optical counterpart with ESO HAWK-I instrument at VLT. The image shows the part of the sky which was checked for possible optical transients related to that event. No counterpart was discovered. Credit: ENGRAVE/ESO (*http://www.engrave-eso.org/NS_BH_Merger/*)

3 LIGO-Virgo O3 Run

Since 2019 April 1, LIGO-Virgo collaboration released 38 non-retracted alerts, most of them (20) related to distant BH-BH binary mergers. The remaining were likely due to NS-NS and BH-NS mergers but most of them were too distant to have their EM counterparts identified. The most promising case was an event detected on 2019 August 14, S190814bv. An intensive search for EM candidates was done by various groups around the world, but no counterpart of the GW event was identified (see, e.g., Andreoni et al., 2019). ENGRAVE collaboration triggered X-Shooter spectroscopy of potential candidates and FORS2 and HAWK-I to identify the candidates (see Fig. 2). The 11 hours of observing time were used for this event. A few triggers have been cancelled because other groups classified them as supernovae or other types of transients not related to GW. Therefore, the hunt is still on-going as new GW events are being discovered and are searched for EM counterparts.

In the coming decade the real game-changer will be a combination of Large

Synoptic Survey Telescope (LSST) – the 8-m wide field of view telescope, and 30-m Extremely Large Telescope (ELT) of ESO. Faint optical counterparts to GW events, not detectable now, will be identified photometrically and studied spectroscopically, providing an insight into the unexplored parts of the Universe.

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