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The Electromagnetic Counterpart of the Gravitational Wave Source GW170817

Invited talk

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Abstract. On 17th August 2017 a strong source of gravitational waves was detected by the LIGO-Virgo collaboration. The signal lasted for 60 seconds, and the event was followed just 2 seconds later by a short burst of gamma-rays that was detected by Fermi and INTEGRAL. The gravitational-wave and gamma-ray source had consistent sky positions to within about 30 square degrees. Within 10 hours of the gravitational-wave source event, a fast fading optical and near-infrared counterpart was discovered, which was subsequently followed-up and studied intensively for several weeks and months by numerous facilities. This talk presented the results from our optical and near-infrared imaging and spectroscopic follow-up campaign of this unprecedented discovery, which was the first electromagnetic counterpart of a gravitational-wave source, the first identification of a neutron star–neutron star merger, and the first direct evidence of the source of r-process elements. It focussed on the results of the GROND and ePESSTO teams, showing that this remarkable transient truly opened up the era of multi-messenger astronomy.

Keywords. Gravitational waves, stars: neutron

1. GW170817

On 2017 August 17 a strong source of gravitational waves (GWs) was detected by the LIGO-Virgo collaboration. An initial sky map of the GW alert, which had a probability of 1 of being a neutron-star–binary merger, marked the first ever GW detection of a neutron star–neutron star merger. The GW signal lasted for 60 seconds, and was followed just 2 seconds later by a short gamma-ray burst that was detected by Fermi and INTEGRAL. The localizations of the GW and the Fermi and INTEGRAL gamma-ray burst detections are shown in Fig. 1, and are consistent to within a position of about 30 square degrees. Just half a day later the One-Meter Two Hemisphere (1M2H) team announced the discovery of a bright optical counterpart. The source was detected by searching for new transients in the 50 or so most massive galaxies nearest to the localization volume (<50 Mpc); the latter was located in the elliptical galaxy NGC 4993. From then on more than 70 ground- and space-based telescopes joined a global observational campaign. Details are given by Abbott *et al.* (2017).

2. Kilonovæ

Theory predicts that there should broad-band electromagnetic radiation emitted when a neutron star–neutron star or neutron star–black hole collide. In addition, a huge amount of heavy r-process elements should subsequently be produced and ejected during the merger process (Li & Paczyński 1998). The thermal emission of the merger ejecta (by radioactivity of r-process elements) can produce emission up to 1000 times brighter than a

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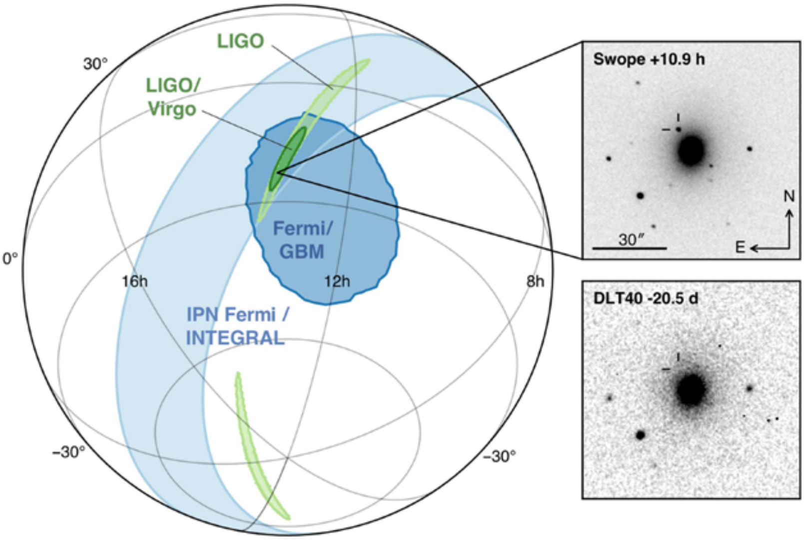

Figure 1. Localization of the gravitational-wave (banana-shaped regions), gamma-ray burst (marked by Fermi/GBM and IPN Fermi/INTEGRAL), and optical counterpart (scale panels) associated with the detected binary neutron-star merger. (*Modified from Abbott et al. 2017.*)

classical nova, thus earning such an event the name ‘kilonova’ (Metzger *et al.* 2010). That strength of emission provides the high-temperature and high neutrino-density environment required for the r-process to occur, and is thus thought to be an important source of heavy elements in the Universe (Lattimer & Schramm 1974; Eichler *et al.* 1989).

3. AT2017gfo

I now focus on our optical and near-infrared (NIR) photometric and spectroscopic data of AT2017gfo – the first electromagnetic counterpart of a binary neutron-star merger and source of GW. Full details of our observations, data reduction and results were presented by Smartt, Chen *et al.* (2017).

Starting on 2017 August 18, we used the Gamma-Ray burst Optical/Near-infrared Detector (GROND; Greiner *et al.* 2008) mounted on the 2.2-m MPG telescope at ESO in Chile, in order to follow up the kilonova AT2017gfo intensively for several weeks. The GROND imager offers simultaneous coverage in g', r', i', z' and JHK_s bands, furnishing a powerful and very efficient instrument with which to follow up transient events. Fig. 2 shows a GROND colour image of the transient AT2017gfo and its host galaxy. The kilonova is the blue point source north-east of the galaxy nucleus. During our observations we witnessed a multi-band temporal evolution of AT2017gfo, which declined rapidly at optical wavelengths (dropping 4 magnitudes in the first 5 days in the g band), and remained initially flat in the NIR bands, eventually steepening after about 7 days beyond the merger event. The 7-band GROND light curves of the kilonova are shown in Fig. 3. We compared the absolute magnitude of AT2017gfo in each band with several kilonova light-curve models, and found that the best fit was provided by the model from Metzger (2017). The model assumes a lower opacity of ejecta from light r-process elements (a blend of elements with atomic numbers $90<A<140$), and includes a hot and blue component in the early emission, called a ‘blue kilonova’.

Furthermore, using our multi-colour data we constructed a bolometric light-curve of AT2017gfo, which is shown in Fig. 4. The peak luminosity of $10^{42.05}$ erg s^{-1} occurred at 0.64 days after the GW detection, assuming a black-body temperature of 7600 ± 2000 K.

Figure 2. GROND colour-combined image of the kilonova AT2017gfo and its host galaxy, NGC 4993 (north is upwards; east is to the left). The kilonova is the blue point source just north-east of the galaxy nucleus. (Data source: ESO/S.J. Smartt & T.-W. Chen).

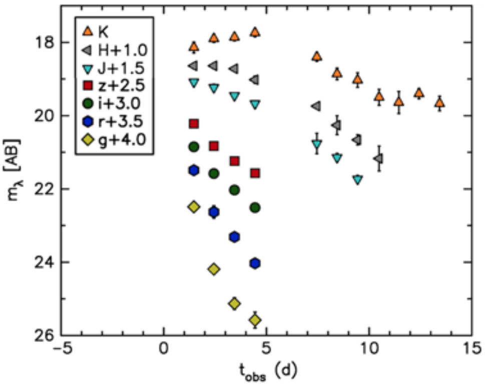

Figure 3. GROND light-curve of AT2017gfo in $g'r'i'z'JHK_s$ bands. The X-axis corresponds to the relative time, in days, since the detection of GW170817 (see Smartt *et al.* 2017).

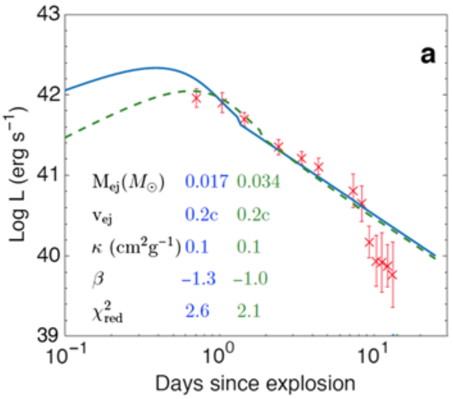

Figure 4. Model fitting and the bolometric light curve of AT2017gfo. Our best-fit model is shown with the solid line; the dashed model also includes a thermalization efficiency. Our best-fit power law was $\beta = -1.0$ to -1.3, which is close to the value of ($\beta = -1.2$) predicted by kilonova radioactivity models. (*Reproduced from Smartt et al., 2017*).

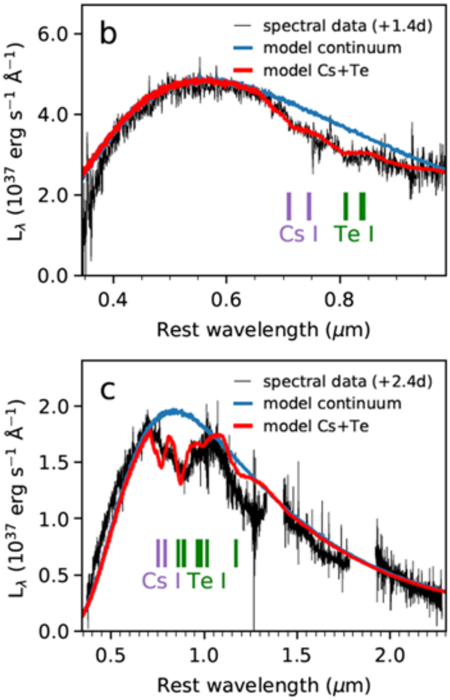

Figure 5. NTT/EFOSC2 and VLT/*X-shooter* spectra of AT2017gfo taken 1.4 and 2.4 days, respectively, after the GW detection. Overplotted are blackbody and blackbody plus absorption models. The evolution of the spectrum of AT2017gfo can be seen clearly between the two spectral epochs and model fits. The absorption features seen in the second epoch may correspond to Cs I and Te I lines in the spectrum. *(Reproduced from Smartt et al., 2017)*.

We fitted the semi-analytic models of Arnett (1982) to our bolometric light-curve, and found that a power source-function term of $\beta = -1.2 \pm 0.3$ provided a good match to the theoretical expectations for *r*-process radioactivity. From our best-fit model we also found a low opacity of $\kappa = 0.1$ cm^2 g^{-1}, indicating that light *r*-process elements are dominant within the ejecta, which has a mass of about 0.04 $M_\odot$. Our best-fit power-law exponent to the bolometric light-curve and the implied ejecta mass are remarkably close to the values predicted from the kilonova models from Metzger (2017).

We obtained spectroscopic observations of AT2017gfo from +1.4 days to +4.4 days after the GW trigger, using the NTT/EFOSC2 (through the ePESSTO project; Smartt *et al.* 2015) and VLT/*X-shooter*. Our two spectral epochs showed rapid evolution. The first spectrum (at +1.4 days after the GW event) shows a featureless blue spectrum with no clear absorption lines such as the Balmer series, Ca II or Si II, which are normally detected in supernova spectra. Our *X-shooter* spectrum (observed at +2.4 days post-event) covers the wavelength range from the near-UV to the NIR. The second spectrum is red and shows strong absorption features. The evolution between the two spectral epochs is shown in Fig. 5. The absorption features present in our *X-shooter* spectrum are probably lines produced by *r*-process elements such as Tellurium (Te I) and Caesium (Cs I).

4. Summary

AT2017gfo is the first unambiguous electromagnetic counterpart of a gravitational-wave source, the first GW detection of a neutron star–neutron star merger, and the first direct evidence that neutron binary mergers are a significant source of *r*-process elements. The accompanying gamma-ray burst and kilonova were detected through the wavelength range gamma-ray, X-ray, UV, optical and infra-red to radio. In a period of just two weeks, this was one of the best observed objects in astronomy's history; more than 70 papers were published on the electromagnetic data alone. The simultaneous optical and NIR observations available with GROND makes the instrument a very powerful one for detecting and monitoring future kilonova events, and ultimately for disentangling the various emission components and corresponding opacities that arise from kilonova events. This remarkable transient truly opened up the era of multi-messenger astronomy.

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