Gravitational Wave Astrophysics: Early Results from Gravitational Wave Searches and Electromagnetic Counterparts
Proceedings IAU Symposium No. 338, 2017
G. González & R. Hynes, eds.

doi:10.1017/S1743921318003630

Observations of the first electromagnetic counterpart to a gravitational wave source by the TOROS collaboration

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Abstract. We present the results of prompt optical follow-up of the electromagnetic counterpart of GW170817 by the Transient Optical Robotic Observatory of the South Collaboration (TOROS). We detected highly significant dimming in the light curves of the counterpart over the course of only 80 minutes of observations obtained ∼35 hr after the trigger with the T80-South telescope. A second epoch of observations, obtained ∼59 hr after the event with the EABA 1.5m telescope, confirms the fast fading nature of the transient. The observed colors of the counterpart suggest that this event was a "blue kilonova" relatively free of lanthanides.

Keywords. Gravitational waves, stars: neutron

1. Introduction

The Transient Optical Robotic Observatory of the South Collaboration (TOROS; Díaz *et al.* 2014) was organized in 2013 to participate in electromagnetic observations of gravitational-wave events recorded by LIGO and Virgo. While seeking to deploy a wide-field optical telescope on Cordón Macón (NW Argentina), we have used other resources for follow-up activities (Colazo *et al.* 2015, Díaz *et al.* 2016).

2. Observations

On 2017 August 18 (∼35 hr after the trigger of GW170817; Abbott *et al.* 2017) we observed the EM counterpart (Coulter *et al.* 2017) using the 0.8-m T80-South telescope (T80-S) at CTIO. We used its 85 Mpix camera (FoV of 1.4° on a side) to obtain 16, 15, and 15 one-minute exposures through SDSS *gri* filters, respectively, over the course of 80 minutes. The left panel of Fig. 1 shows a color composite of a small sub-section of the T80S FoV centered on the transient.

On 2017 August 19 (∼59 hr after the GW trigger) we imaged the source with the 1.54-m telescope at the Estación Astrofísica de Bosque Alegre (EABA) and a 17 Mpix camera with a FoV of 17′ on a side. We obtained 88 one-minute unfiltered exposures.

3. Photometry

We subtracted NGC 4993 from all of the images by fitting a Sérsic profile with IMFIT (Erwin 2015). The right panel of Fig. 1 shows the result. We carried out time-series

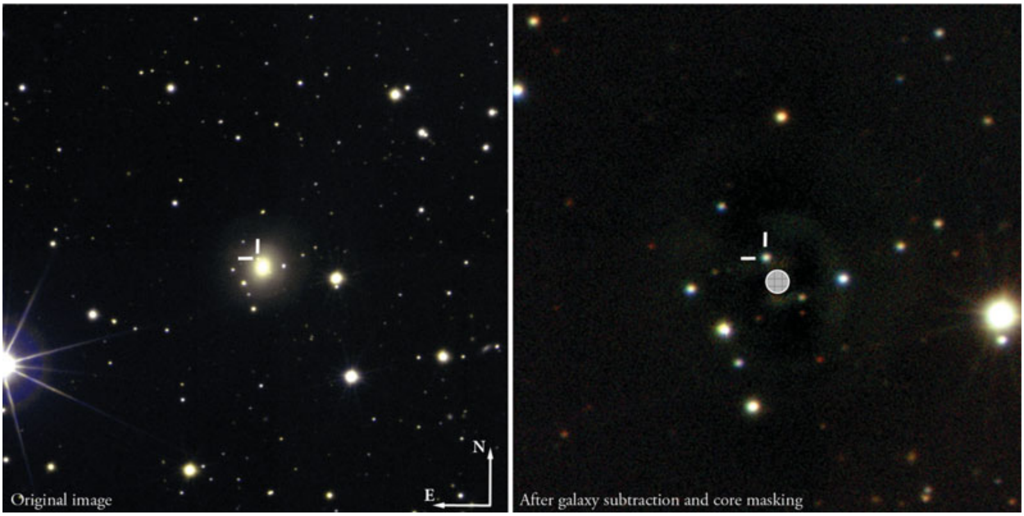

Figure 1. Left: pseudo-color image of a small subsection (2.4′ on a side) of the FoV of T80-S, centered on the transient (marked with crosshairs). Intensity scaling is logarithmic in order to better display the light distribution of the host galaxy. Right: residual image after host galaxy subtraction and core masking (hatched circle).

PSF photometry of the T80-S images using DAOPHOT, ALLSTAR, and ALLFRAME (Stetson 1987, Stetson 1994) following the procedures described in Macri *et al.* (2015).

We identified 100 bright & isolated stars in each filter within the T80-S FoV and solved for frame-to-frame offsets to correct for differential extinction and any other variations. We achieved a precision in our time-series photometry of 0.01 mag or better for objects with $g < 16$, $r < 15$, $i < 14$ mag.

We transformed the T80-S measurements into the Pan-STARRS1 photometric system (Tonry *et al.* 2012) and simultaneously corrected for atmospheric extinction using 4600−5400 stars in common between our star lists and the PS1 catalog. The calibrated light curves are plotted in Fig. 2. The photometric measurements are reported in Table 1 of Diaz *et al.* (2017), which contains additional details of our observations and analysis.

Due to the lower S/N of the EABA observations, we combined those frames to obtain a mean PSF magnitude. We transformed it to PS1 r using 200 stars in common.

4. Analysis

The T80-S light curve of the transient exhibits a very significant decline across all bands during the ∼80 min of observations. A weighted linear fit to the data yields $\Delta g = 0.17 \pm 0.03$ mag, $\Delta r = 0.14 \pm 0.02$ mag, $\Delta i = 0.10 \pm 0.03$ mag over that time period. The mean magnitudes at the mid-point of our observations (1.467 days after the GW trigger) and their time derivatives are:

$$\begin{aligned} g &= 18.60 \pm 0.02 \text{ mag}, & dg/dt &= 3.0 \pm 0.6 \text{ mag/day} \\ r &= 17.99 \pm 0.02, & dr/dt &= 2.5 \pm 0.4 \\ i &= 17.80 \pm 0.02, & di/dt &= 1.9 \pm 0.5 \end{aligned}$$

As we do not have a measurement of $r-i$ during the EABA observations, we present two possible values for its calibrated magnitude at that time (2.456 days after the GW trigger): $r = 18.78 \pm 0.03$ mag if its color did not evolve over 24 hr or $r = 19.15 \pm 0.06$ mag

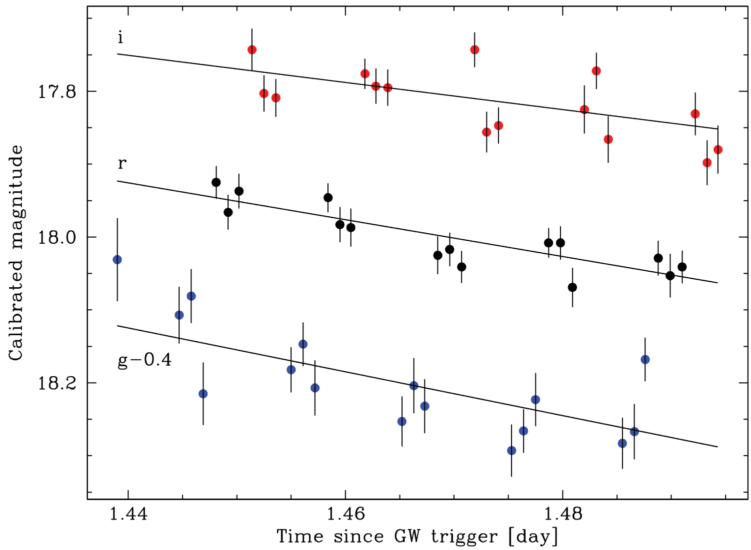

Figure 2. *gri* light curves of the EM counterpart to GW170817, obtained with T80-S on 2017 August 18. The *g* points have been offset by −0.4 mag for clarity.

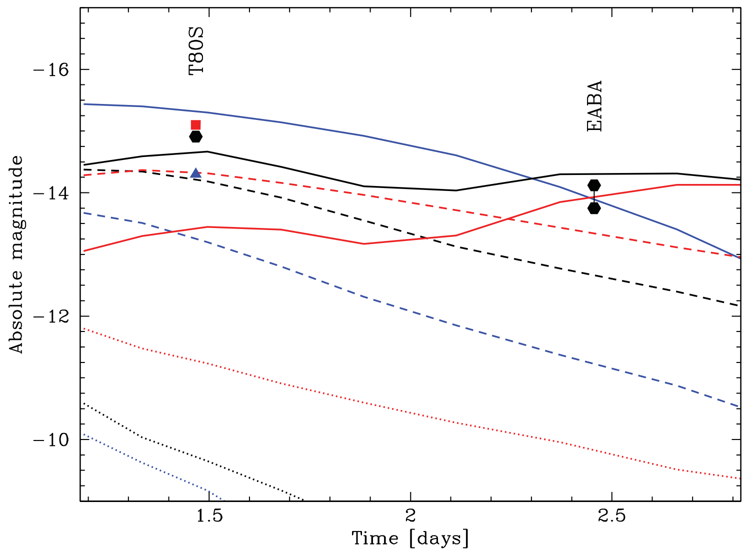

Figure 3. Comparison of our photometry corrected for $D = 38$ Mpc (g: blue; r: black; i: red) with models from Tanaka *et al.* (2018). The dotted lines represent a "red kilonova" model with dynamical ejecta rich in lanthanides. The dashed and solid lines represent "blue kilonova" wind models with decreasing amounts of lanthanides. The measurement uncertainties are smaller than the size of the symbols. The two possible r values at 2.456 days are described in the text.

if its color evolved as extrapolated from the T80-S light curves to $r{-}i \sim 0.84 \pm 0.08$ mag. Despite these limitations, the EABA observations confirm a fast decline of $\Delta r = 0.8 - 1.2$ mag over 24 hr.

Fig. 3 compares our colors and absolute magnitudes (adopting $D = 38 \pm 5$ Mpc, Kourkchi & Tully 2017) with models from Tanaka *et al.* (2018). The measurements are inconsistent with the predictions for a "red kilonova" containing dynamical ejecta

https://doi.org/10.1017/S1743921318003630 Published online by Cambridge University Press

($0.01\ M_\odot$, $v = 0.2c$) rich in lanthanides (dotted lines). Our r-band luminosity is in fairly good agreement with the prediction for a "blue kilonova" (Metzger 2017) model with a wind ($0.01\ M_\odot$, $v = 0.05c$) free of lanthanides ($Y_e = 0.3$ variant, solid lines), but the predicted $g-i$ color at $t = 1.5$ days does not match the observations. A similar model in which the ejecta contain a small amount of lanthanides ($Y_e = 0.25$ variant, dashed lines), matches the observed colors fairly well, but the predicted luminosities are somewhat lower than observed. Regardless, it appears that this event may have been relatively free of lanthanides.

References

Abbott, B. P., *et al.* 2017, *PRL* 116, 061102
Colazo, C., *et al.* 2015, *GRB Coordinates Network, Circular Service,* 18338
Coulter, D. A., *et al.* 2017, *GRB Coordinates Network, Circular Service,* 21529
Díaz, M. C., *et al.* 2014, in *Third "Hot-wiring the Transient Universe" Workshop*, 225
Díaz, M. C., *et al.* 2016, *ApJL* 828, 16
Diaz, M. C. *et al.* 2017, *ApJL* 848, 29
Erwin, P. 2015, *ApJ* 799, 226
Kourkchi, E. & Tully, R. B. 2017, *ApJ* 843, 16
Macri, L. M., *et al.* 2015, *AJ* 149, 117
Metzger, B. D. 2017, *LRR* 20, 3
Stetson, P. B. 1987, *PASP* 99, 191
Stetson, P. B. 1994, *PASP* 106, 250
Tanaka, M., *et al.* 2018, *ApJ* 852, 109
Tonry, J. L., *et al.* 2012, *ApJ* 750, 99