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A comparison between SALT/SAAO observations and kilonova models for AT 2017gfo: the first electromagnetic counterpart of a gravitational wave transient – GW170817

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ABSTRACT

We report on SALT low-resolution optical spectroscopy and optical/IR photometry undertaken with other SAAO telescopes (MASTER-SAAO and IRSF) of the kilonova AT 2017gfo (a.k.a. SSS17a) in the galaxy NGC4993 during the first 10 d of discovery. This event has been identified as the first ever electromagnetic counterpart of a gravitational wave event, namely GW170817, which was detected by the LIGO and Virgo gravitational wave observatories. The event is likely due to a merger of two neutron stars, resulting in a kilonova explosion. SALT was the third observatory to obtain spectroscopy of AT 2017gfo and the first spectrum, 1.2 d after the merger, is quite blue and shows some broad features, but no identifiable spectral lines and becomes redder by the second night. We compare the spectral and photometric evolution with recent kilonova simulations and conclude that they are in qualitative agreement for post-merger wind models with proton:nucleon ratios of $Y_e = 0.25$–0.30. The blue colour of the first spectrum is consistent with the lower opacity of the lanthanide-free *r*-process elements in the ejecta. Differences between the models and observations are likely due to the choice of system parameters combined with the absence of atomic data for more elements in the ejecta models.

Key words: gravitational waves – nuclear reactions, nucleosynthesis, abundances – binaries: close – gamma-ray burst: individual: GRB 170817A – stars: neutron – stars: winds, outflows.

1 INTRODUCTION

Following the advanced LIGO detection of the gravitational wave transient, GW170817/G298048 (LIGO Scientific Collaboration and Virgo Collaboration 2017; Abbott et al. 2017a) and its near

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Table 1. Observing details.

Date (2017)	Start time (UTC)	Obs type	Telescope	Filter/bandpass	Exp time (s)	Mag/error (AB system)	Conditions[a] (arcsec)	Delay[b] (d)
18 Aug	17:07:20	Spec	SALT	3750−9600 Å	433	–	Cirrus; 1.2	1.19
18 Aug	17:06:55	Phot	MASTER-SAAO	*W*	1080	17.3 ± 0.2	Cirrus; 1.2	1.19
18 Aug	17:17:33	Phot	MASTER-SAAO	*R*	540	17.0 ± 0.2	Cirrus; 1.2	1.20
18 Aug	17:34:04	Phot	MASTER-SAAO	*B*	540	18.1 ± 0.1	Cirrus; 1.2	1.21
19 Aug	16:58:32	Spec	SALT	3750−9600 Å	716	–	Clear; 1.2	2.18
19 Aug	17:06:57	Phot	MASTER-SAAO	*W*	1080	18.4 ± 0.2	Clear; 1.2	2.19
19 Aug	17:53:34	Phot	MASTER-SAAO	*R*	540	18.0 ± 0.3	Clear; 1.2	2.22
20 Aug	17:04:36	Phot	MASTER-SAAO	*W*	540	>19.1	Cirrus; 1.1	3.19
20 Aug	17:25:56	Phot	MASTER-SAAO	*R*	540	>18.6	Cirrus; 1.1	3.20
20 Aug	17:36:32	Phot	MASTER-SAAO	*B*	540	>19.3	Cirrus; 1.1	3.21
21 Aug	17:08:14	Phot	MASTER-SAAO	*W*	540	>19.1	Cirrus; 1.5	4.19
21 Aug	18:06:12	Phot	MASTER-SAAO	*R*	540	>18.6	Cirrus; 1.5	4.23
21 Aug	19:20:23	Phot	MASTER-SAAO	*B*	540	>18.3	Cirrus; 1.5	4.27
23 Aug	17:22	Phot	IRSF	*J*	1800	18.65 ± 0.19	Clear; 1.5	6.20
23 Aug	17:22	Phot	IRSF	*H*	1800	18.60 ± 0.18	Clear; 1.5	6.20
23 Aug	17:22	Phot	IRSF	*K*	1800	18.01 ± 0.10	Clear; 1.5	6.20
24 Aug	16:51	Phot	IRSF	*J*	2400	18.95 ± 0.32	Clear	7.17
24 Aug	16:51	Phot	IRSF	*H*	2400	18.53 ± 0.17	Clear	7.17
24 Aug	16:51	Phot	IRSF	*K*	2400	18.02 ± 0.12	Clear	7.17
26 Aug	16:57	Phot	IRSF	*J*	3000	18.87 ± 0.30	Clear; 1.3	9.18
26 Aug	16:57	Phot	IRSF	*H*	3000	18.82 ± 0.23	Clear; 1.3	9.18
26 Aug	16:57	Phot	IRSF	*K*	3000	18.25 ± 0.25	Clear; 1.3	9.18

Notes. [a]Transparency; seeing.
[b]Since GW trigger time: 2017 August 17, 12h41m04s UTC.

simultaneous detection as a short gamma-ray burst by the *Fermi* GBM and INTEGRAL (Goldstein et al. 2017; Savchenko et al. 2017), the optical counterpart was first identified by Coulter et al. (2017) as a point source, located ∼10 arcsec from the centre of the S0 galaxy, NGC4993, initially named SSS17a and then renamed AT 2017gfo, following the IAU naming convention.

The source was independently identified and observed by several groups following the refinement of the error position provided by the LIGO/Virgo G298048 BAYESTAR HLV map (LIGO Scientific Collaboration and Virgo Collaboration 2017). The results of these multiwavelength studies are published in a number of key papers (Abbott et al. 2017b; Arcavi et al. 2017; Cowperthwaite et al. 2017; Evans et al. 2017; Pian et al. 2017; Shappee et al. 2017; Smartt et al. 2017; Tanvir et al. 2017; Valenti et al. 2017). The optical transient of GW170817 was subsequently identified to be a kilonova (Kasliwal et al. 2017; McCully et al. 2017; Nicholl et al. 2017; Tanaka et al. 2017b; Tanvir et al. 2017), the remnant of a neutron star–neutron star (hereafter abbreviated as NS) merger (e.g. Eichler et al. 1989). Evidence of kilonovae remnants of NS mergers have been presented before the GW170817 event (e.g. Tanvir et al. 2013). The radioactive decay of *r*-process elements in the expanding wind or envelope of a kilonova has been postulated to explain the energetics plus spectral and photometric evolution (e.g. Li & Paczyński 1998; Rosswog et al. 1999, 2005; Freiburghaus, Rosswog & Thielemann 1999; Metzger et al. 2010; Barnes et al. 2016; Coughlin et al. 2017; Kasen et al. 2017; Tanaka & Hotokezaka 2013; Tanaka et al. 2017b).

In this paper, we show the SALT spectra of the kilonova, AT 2017gfo, taken, respectively, at 1.2 and 2.2 d after the GW trigger (at 12h 41m 04s UTC on 2017 August 17), and compare them to the three different models developed by Tanaka et al. (2017a) for kilonova ejecta. These models have varying degrees of opacity and abundances of the lanthanide *r*-process elements. The flux and the blue nature of the first SALT spectrum seems to be most consistent with the ‘blue’ kilonova wind model, with a proton/nucleon ratio of $Y_e = 0.30$, for the assumed distance of 40 Mpc. We also present photometry of AT 2017gfo over a period 10 d post detection, in optical (*B*, *V* and *R*) and infrared (*J*, *H* and *K*), derived from the MASTER-SAAO and IRSF telescopes at Sutherland, respectively. We again compare these results to the respective kilonova model predictions, and conclude that either the $Y_e = 0.25$ or 0.30 wind models are qualitatively similar to the observed magnitudes.

2 SALT AND SAAO OBSERVATIONS

Following the detection of AT 2017gfo, the optical counterpart to GW170817, director’s discretionary time observations (programme 2017-1-DDT-009) were undertaken on 2017 August 18 and 19 on the Southern African Large Telescope (SALT; Buckley et al. 2006). The observations were taken with the prime focus Robert Stobie spectrograph (Burgh et al. 2003), beginning in twilight and proceeding until the end of the available telescope track time. A third attempt on August 20 resulted in no meaningful data being obtained due to the sky brightness coupled with the degree of fading of the kilonova. The observational details are included in Table 1, and preliminary reports on the results are presented in Shara et al. (2017), Abbott et al. (2017b), McCully et al. (2017) and Andreoni et al. (2017).

The low-resolution PG300 surface relief transmission grating was used, rotated to an angle of 5.75°, with a long slit of width 2 arcsec, which implies an ∼88 per cent slit throughput in the given seeing conditions. The spectra had a resolution which varied from $R \sim 150$ (at ∼3750 Å) to ∼400 (at ∼9600 Å), with a mean of $R \sim 380$. The observations were reduced using the PySALT package (Crawford et al. 2010), which accounts for basic CCD characteristics (cross-talk, bias and gain correction) and removal of cosmic rays, wavelength calibration, and relative flux calibration. Additional reductions to account for accurate sky and galaxy background removal were done using standard IRAF routines.

Because of the SALT design, which has a moving, field-dependent and underfilled entrance pupil, absolute flux calibration with SALT is difficult to achieve with a good degree of accuracy, which at best is ±20 per cent. Observations were taken in morning twilight on 2017 August 18 of the spectrophotometric standard star EG21, which was used to determine a relative flux calibration on both nights. The spectral fluxes were then corrected by convolving the observed spectra with standard Johnson–Cousins B and R filters and comparing the results with B and R observations taken simultaneously with the MASTER-SAAO facility, which are included in Table 1, corrected for Milky Way extinction, as presented in Lipunov et al. (2017). This comparison implied that the spectra were required to be adjusted in flux by a multiplicative constant of 2.04 and 2.4, respectively, on the two nights.

MASTER-SAAO also observed AT 2016gfo in a filter-less mode on several nights, defined as W (see Table 1), which is between the B and V filters, depending on the object colour (e.g. Lipunov et al. 2010). AT 2017gfo was also observed by the SAAO 1.0 m Elizabeth telescope, however the data quality was too poor to estimate meaningful magnitudes.

Details of the infrared observations of AT 2017gfo using the Infrared Survey Facility (IRSF) and the data reduction are described in Kasliwal et al. (2017). The near-infrared (J, H and K_s) simultaneous imaging camera, SIRIUS, installed on the 1.4 m IRSF telescope was used in the period 2017 August 23–26, up to 9.2 d after the GW trigger time. A total of 10 dithered exposures of 30 s each with dithering radius of 60 arcsec per observing sequence, respectively, were observed and repeated typically 7–8 times to obtain a good S/N ratio. Dark frames were obtained at the end of the nights and twilight flat-field frames were obtained before and after the observations. The data reduction includes dark frame subtraction, flat-field correction, sky-subtraction, dither combination and astrometric calibration, and was carried out using the SIRIUS data reduction pipeline software. The photometry was corrected for Milky Way extinction as in Kasliwal et al. (2017).

Care was taken to account for the contamination by the host galaxy when undertaking the photometry of AT 2017gfo. A median filtered image subtraction technique was applied to the IRSF images to remove the extended galaxy emission, as done by Kasliwal et al. (2017). While the formal uncertainties for the IRSF *JHK* photometric measurements were typically 0.1−0.2 mag (see Table 1), there could well be additional systematic errors due to the difficulty of removing the effects of the nearby galaxy. We do note, however, that our measurements are within ±0.1 mag of those reported by Tanvir et al. (2017) for VISTA J and K observations taken 6−7 h after our IRSF observation on 2017 August 23 and 24.

3 COMPARISON OF OBSERVED SPECTRA TO KILONOVA MODELS

Like for the other early-time (t = 0.5−1.4 d) spectra (Andreoni et al. 2017; Shappee et al. 2017; Smartt et al. 2017), the first SALT spectrum (t = 1.19 d) is blue, peaking at ∼4500 Å, which is also consistent with the *Swift* UV observations (Evans et al. 2017). The second SALT observation (t = 2.18 d), although much noisier due to a relatively higher sky background, showed a distinct reddening, with the peak flux at ∼6800 Å, consistent with the results of Smartt et al. (2017), Pian et al. (2017) and McCully et al. (2017). All of these results have been qualitatively explained in terms of kilonova models involving post-merger wind ejecta (e.g. Kasen et al. 2017; Tanaka et al. 2017a), which rapidly cools (over time-scales of days), shifting the peak of the SED from blue to red.

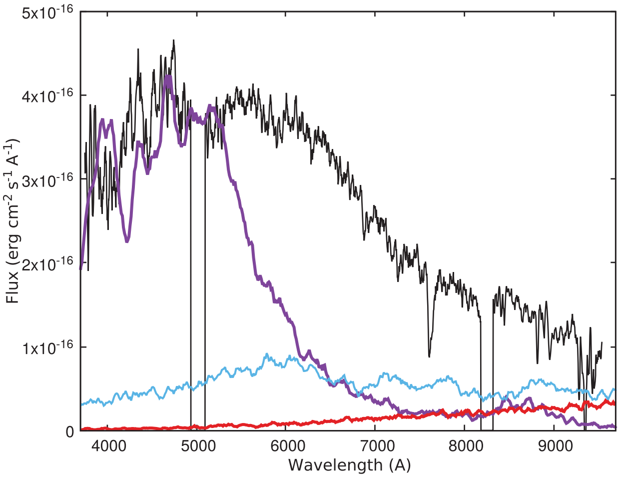

Figure 1. Comparison of the first SALT spectrum of AT 2017gfo, obtained 1.2 d after the GW event (in black), with two merger wind models of Tanaka et al. (2017a), namely $Y_e = 0.30$ (purple) and $Y_e = 0.25$ (blue), and for 1.5 d after a kilonova explosion, scaled to a distance of 40 Mpc. For comparison, the higher velocity dynamical ejector model, APR4-1215, (Tanaka et al. 2017a) is shown for comparison (red curve).The gaps in the SALT spectra at ∼5000 and 8200 Å are due to CCD gaps.

Following the merger of two neutron stars, the cause of the GW170817 event (e.g. Abbott et al. 2017a), material is ejected in a kilonova explosion (also referred to as macronova), whose luminosity is powered by the radioactive decay of r-process nuclei (Kasen et al. 2017; Tanaka et al. 2017a). Here, we compare our two SALT spectra to the recently derived dynamical ejection models and high-Y_e (Y_e = proton:nucleon ratio, or electron fraction) models of post-merger ejecta by Tanaka et al. (2017a), for delay times of 1.5 and 3.5 d following a kilonova explosion. We have determined the predicted flux densities using the model luminosities together with the assumed distance to NGC 4993/AT 2017gfo of 40 ± 8 Mpc (e.g. Abbott et al. 2017b). Two other studies of NGC4993 have independently confirmed its distance: Hjorth et al. (2017, 41.0 ± 3.1 Mpc), Im et al. (2017, 37.7 ± 8.7 Mpc). It would appear that the dynamical ejecta model, APR4-1215 (Hotokezaka et al. 2013; Tanaka & Hotokezaka 2013; Tanaka et al. 2017a), for two merging NSs of 1.2 and 1.5 $M_\odot$ and ejecta mass of $M_{ej} = 0.01\ M_\odot$, is both too red and too underluminous compared to the observations (see the red curve in Fig. 1). The lower velocity ($v = 0.05c$) post-merger ejecta model, also with $M_{ej} = 0.01\ M_\odot$, but with $Y_e = 0.3$, qualitatively matches the observed flux for $\lambda < 5200$ Å, while there is a deficit of flux at longer wavelengths.

The second SALT spectrum, taken 2.2 d following the GW event, is shown in Fig. 2, together with the same respective models used previously, but for 3.5 d post-merger (these were the next oldest models after t = 1.5 d). These models are a poorer match to the data, although they are ∼1.3 d older than the observations. Since the models for t = 1.5 d are closer in time to the observations (∼0.7 d younger), we show the $Y_e = 0.25$, t = 1.5 d model as well, which is a closer match to the observation both in flux and colour.

These results support the conclusions (e.g. Tanaka et al. 2017b; Tanvir et al. 2017) that dynamical ejecta, with significant abundances of r-process lanthanide elements, confined to the NS−NS orbital plane, is not responsible for the observed SED shape or

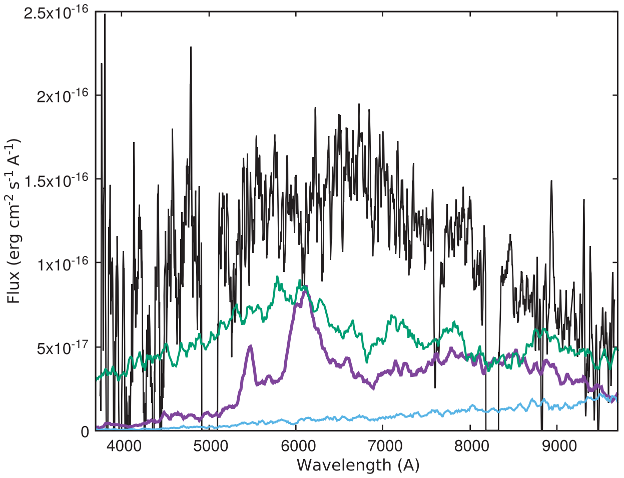

Figure 2. Similar plot to Fig. 1, comparing the second SALT spectrum of AT 2017gfo, obtained 2.2 d after the GW event (in black), with two wind models of Tanaka et al. (2017a), namely $Y_e = 0.30$ (purple) and $Y_e = 0.25$ (blue), for 3.5 d after a kilonova explosion, scaled to a distance of 40 Mpc. In addition, we show the $Y_e = 0.25$, $t = 1.5$ d model (green), which is closer in delay time to the observation.

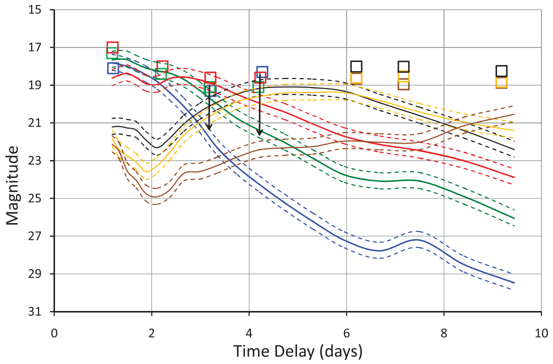

Figure 3. Comparison of optical/IR photometry of AT 2017gfo, obtained during the first ∼10 d after the GW event, with the $Y_e = 0.30$ kilonova wind model of Tanaka et al. (2017a). The solid lines are the predicted magnitudes based on a distance of $d = 40$ Mpc, while the dashed lines represent a ±8 Mpc distance uncertainty. The observed magnitudes and models are colour-coded for *B* (blue), *V*/*W* (green), *R* (red), *JHK* (brown/yellow/black), while the arrows indicate brightness upper limits for *BVR* measurements made after $t = 3$ d. Errors are typically half the size of the box symbols.

spectral evolution of the kilonova. Rather, lanthanide-free material is ejected out of the orbital plane in a wind, which is viewed at an angle of ∼30° to the rotation/GRB jet axis (Kasliwal et al. 2017).

4 COMPARISON OF OBSERVED MAGNITUDES TO KILONOVA MODELS

We undertook a similar comparison between the kilonova models of Tanaka et al. (2017a) and the optical-IR photometry of AT 2017gfo, taken at the SAAO during the first ∼10 d of the kilonova outburst (Figs 3 and 4), assuming a 40 Mpc distance.

In general, it appears that the models are somewhat underluminous in comparison with the observations. While the $Y_e = 0.30$ model (Fig. 3) is in better agreement with the observed magnitudes, particularly in the optical region, the $Y_e = 0.25$ model (Fig. 4) seems to show an overall better agreement if the model was ∼1.5 magnitudes brighter. These discrepancies are likely due to different values for key parameters (e.g. masses of the NSs and ejecta) and missing elements in the models.

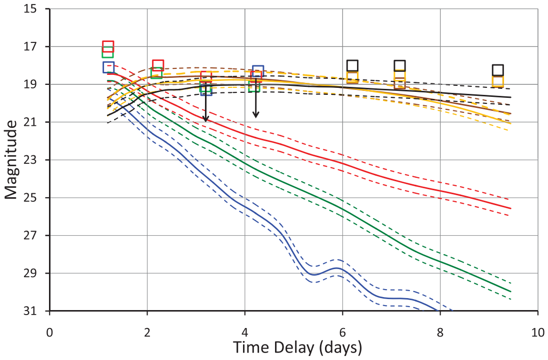

Figure 4. Same as Fig. 3, but compared to the $Y_e = 0.25$ kilonova wind model of Tanaka et al. (2017a).

5 CONCLUSIONS

We have presented optical and infrared observations from SALT and SAAO of the first optical counterpart (AT 2017gfo) of a gravitational wave source, GW170817, a kilonova explosion resulting from the merger of two neutron stars.

SALT was the third observatory to undertake optical spectroscopy of AT 2017gfo (Abbott et al. 2017a; Andreoni et al. 2017). Our early-time (1.2–2.2 d) SALT spectra shows a relatively blue object, which is broadly consistent with the post-merger kilonova ejection models of Tanaka et al. (2017a). The relatively blue colours are also consistent with the lower opacity of the lathanide-free *r*-process elements in the ejecta, although all of the expected features due to *r*-process elements are not seen. In comparing our spectroscopic and photometric measurements to the kilonova models of Tanaka et al. (2017a), we have concluded that there is qualitative agreement with the models invoking post-merger ejection of material out of the orbital plane. However, neither of these models match the observed spectra in their entirety. While the $Y_e = 0.30$ model seems to better match the initial spectral shape and energetics, at least in the blue, the photometric evolution is closer the the $Y_e = 0.25$ model predictions, notwithstanding that the fluxes are too low by a factor ∼4 for the assumed distance of 40 Mpc. Recently, Tanaka et al. (2017b) also concluded that the $Y_e = 0.25$ model was a better match to photometry they reported of AT 2017gfo, which extended to $t = 15$ d after merger.

These models predict an initial blue spectral energy distribution followed by strong wavelength-dependent dimming after the kilonova explosion, which are consistent with our optical/IR photometric observations. In particular, while at optical wavelengths (*BVR*) there is a significant dimming over a time-scale of ∼2–3 d, the *JHK* fluxes remained fairly constant, at least up to ∼9 d following the kilonova eruption.

The detection of an electromagnetic counterpart to a gravitational wave source, coming only ∼2 yr after the first gravitational wave detection, bodes well for the study of future GW neutron star merger events. The ability of SALT to respond promptly and appropriately to transient alerts, in this case the GW170817 event, is one reason for the success of the observations reported here and will hopefully result in similar successes in the future.

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