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The Cow: discovery of a luminous, hot and rapidly evolving transient

S. J. Prentice,1 K. Maguire,1 S. J. Smartt,1 M. R. Magee,1 P. Schady,2 S. Sim,1 T.-W. Chen,2 P. Clark,1 C. Colin,3,1 M. Fulton,1 O. McBrien,1 D. O’Neill,1 K. W. Smith,1 C. Ashall,4 K. C. Chambers,5 L. Denneau,5 H. A. Flewelling,5 A. Heinze,5 T. W.-S. Holoien,6 M. E. Huber,5 C. S. Kochanek,7,8 P. A. Mazzali,9,10 J. L. Prieto,11,12 A. Rest,13,14 B. J. Shappee,5 B. Stalder,15 K. Z. Stanek,7 M. D. Stritzinger,16 T. A. Thompson,7,8 and J. L. Tonry5

1Astrophysics Research Centre, School of Mathematics and Physics, Queen’s University Belfast, BT7 1NN, UK
2Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstraße, 85748, Garching, Germany
3Université de Pierre et Marie Curie (Paris IV), 4 Place Jussieu, 75252, Paris Cedex 5, France
4Department of Physics, Florida State University 77 Chiefhane Way, Tallahassee 32304, USA
5Institute for Astronomy, University of Hawai’i, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
6The Observatories of the Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101, USA
7Department of Astronomy, The Ohio State University, 140 W. 18th Ave., Columbus, OH 43210, USA
8Center for Cosmology and AstroParticle Physics, The Ohio State University, 191 W. Woodruff Ave., Columbus, OH 43210, USA
9Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool Science Park, 146 Brownlow Hill, Liverpool, L3 5RF, UK
10Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85748 Garching, Germany
11Núcleo de Astronomía de la Facultad de Ingeniería, Universidad Diego Portales, Av. Ejército 441, Santiago, Chile
12Millennium Institute of Astrophysics, Santiago, Chile
13Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
14Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
15LSST, 950 N Cherry Ave, Tucson, AZ 95719
16Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark

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ABSTRACT

We present the ATLAS discovery and initial analysis of the first 18 days of the unusual transient event, ATLAS18qqn/AT2018cow. It is characterized by a high peak luminosity (∼1.7 × 1044 erg s⁻¹), rapidly evolving light curves (>5 mag rise to peak in ∼3.5 days), and hot blackbody spectra, peaking at ∼27000 K that are relatively featureless and unchanging over the first two weeks. The bolometric light curve cannot be powered by radioactive decay under realistic assumptions. The detection of high-energy emission may suggest a central engine as the powering source. Using a magnetar model, we estimated an ejected mass of 0.1−0.4 M⊙, which lies between that of low-energy core-collapse events and the kilonova, AT2017gfo. The spectra cooled rapidly from 27000 to 15000 K in just over 2 weeks but remained smooth and featureless. Broad and shallow emission lines appear after about 20 days, and we tentatively identify them as He i although they would be redshifted from their rest wavelengths. We rule out that there are any features in the spectra due to intermediate mass elements up to and including the Fe-group. The presence of r-process elements cannot be ruled out. If these lines are due to He, then we suggest a low-mass star with residual He as a potential progenitor. Alternatively, models of magnetars formed in neutron-star mergers give plausible matches to the data.

Corresponding author: Simon Prentice
sipren.astro@gmail.com
1. INTRODUCTION

The advent of wide-field transient surveys that scan the visible sky every few nights has led to the discovery of new classes of transients, such as superluminous supernovae (SLSNe, e.g., Quimby et al. 2011), Type Iax SNe (e.g. Li et al. 2003), and Ca-rich transients (e.g. Perets et al. 2010). In particular, high-cadence surveys have uncovered a new parameter space of SN-like events that rise and fall much faster than standard SNe (e.g. Drout et al. 2014; Arcavi et al. 2016; Tanaka et al. 2016; Pursiainen et al. 2018; Rest et al. 2018). The first confirmed kilonova (AT2017gfo) from a neutron star merger detected in gravitational waves (GW170817) is the fastest declining astrophysical transient (Abbott et al. 2017) that also approaches SN-like luminosities.

These newly discovered rapidly evolving transients have a wide range of peak absolute magnitudes ($−15 < M < −22$ mag), rise times (∼1–10 days), and spectral properties that make them difficult to explain through a single progenitor scenario but most are incompatible with a radioactively-powered explosion. Proposed scenarios include SN shock breakout in a surrounding wind (e.g. Ofek et al. 2010), cooling low-mass envelopes after a SN shock breakout (Nakar & Sari 2010; Kleiser & Kasen 2014), a magnetar-powered binary neutron star merger (Gao et al. 2013; Yu et al. 2013; Metzger & Piro 2014), and an optical flare from a tidal disruption event (Strubbe & Quataert 2009).

In this Letter, we report the discovery of the unusual, luminous, and fast-evolving transient, ATLAS18qqn (nicknamed ‘The Cow’) discovered by the ATLAS survey (Tonry et al. 2018). We present initial observations from ultra-violet (UV) to near-infrared (NIR) wavelengths out to ∼18–24 days post discovery. ATLAS18qqn was also detected in the X-ray, radio, and sub-millimeter (e.g., Rivera Sandoval et al. 2018; de Ugarte Postigo et al. 2018) but these observations are not the focus of this paper.

2. OBSERVATIONS AND DATA ANALYSIS

ATLAS is a twin 0.5-m telescope system installed on the Hawai’ian islands of Haleakala and Mauna Loa (Tonry et al. 2018). Each unit has a 28.9 square degree field of view that is robotically surveying the sky in cyan ($c$) and orange ($o$) filters that are broadly equivalent to Pan-STARRS/Sloan Digital Sky Survey (SDSS) $g+r$ and $r+i$ filters, respectively. ATLAS typically covers the whole sky visible from Hawaii every two nights. We discovered a new transient, ATLAS18qqn, in a 30-second exposure with start time 2018-06-16 10:35:38 UT Modified Julian Date (MJD) 58285.44141 at an AB magnitude of $o = 14.74 ± 0.10$. It was assigned the International Astronomical Union1 name AT2018cow and announced as an unusual transient by Smartt et al. (2018).

AT2018cow is offset by 1.7 kpc from the core of the galaxy CGCG 137-068 (Figure 1). A SDSS DR6 spectrum (Adelman-McCarthy et al. 2008; Smee et al. 2013) shows the galaxy to be star-forming with nebular emission lines at a redshift of $z = 0.014145$. A cosmology with $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, gives a distance of 66±5 Mpc. We corrected for Milky Way (MW) extinction of $E(B−V)_{\text{MW}} = 0.08$ mag (Schlafly & Finkbeiner 2011) using a Cardelli et al. (1989) $R_V = 3.1$ extinction law. We assume that the host galaxy extinction is negligible.

ATLAS did not detect the source 3.95 days2 prior to the first detection to a depth of $>20.2$ mag (3σ limit in o band). The All Sky Automated Survey for Supernovae (ASAS-SN, Shappee et al. 2014) did not detect the source to a depth of $>18.9$ mag (3σ limit in g band) just 1.3 days before the ATLAS detection and robustly detected the source 3 days later (see Table 1). The explosion epoch was estimated from modelling of the bolometric light curve (see Section 4) to be MJD 58284.3, with the ASAS-SN non-detection 0.2 days before.

2.1. Light curves

We began monitoring AT2018cow starting 1.7 days after discovery (Chen & Rabus 2018; Chen & Schady 2018) in $g'+r'+i'z'JHK$ with GROND (Greiner et al. 2008) on the 2.2-m MPG telescope and then in $ugriz$ with IO:O on the Liverpool Telescope (LT; Steele et al. 2004) beginning 4.6 days after discovery. The optical and NIR data were calibrated using SDSS and 2MASS stars (Krühler et al. 2008). Observations with the UV Optical Telescope (UVOT; Roming et al. 2005) on board the Neil Gehrels Swift Observatory (Gehrels et al. 2004) were also obtained and were calibrated using standard procedures (Poole et al. 2008).

Fig. 2 shows the multi-color light curves of AT2018cow. Maximum light occurred on MJD 58286.9 (from the light curve models, see Section 4). An ATLAS data point obtained +0.6 days from maximum has $m_c = 13.6$ mag ($−20.5$ mag, uncorrected for MW ex-

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1 https://wis-tns.weizmann.ac.il/
2 Times denoted in “days” are observer frame, those in “d” in rest-frame.
narrow emission feature consistent with the rest wave-
length of Hα is extended leading us to conclude the emis-
sion feature in these early spectra results from the host
galaxy and not AT2018cow.

The early-time spectra are blue and quite featureless,
as first suggested by Perley (2018). Little evolution is
seen in the spectra up to \( \sim 2 \) weeks after explosion, apart
from a decrease in temperature. It was initially sug-
gested that AT2018cow was spectroscopically similar to
a broad-line Type Ic SN after subtraction of a power-law
component (Xu et al. 2018; Izzo et al. 2018). We find
that the power-law subtracted spectra of AT2018cow do
not evolve similarly to the spectra of GRB-SN 1998bw
(e.g. Galama et al. 1998; Patat et al. 2001). Perley et al.
(2018) also present an extensive follow-up data set of
AT2018cow, finding similar conclusions.

At 21.1 d after detection (\( t = 22.2 \) d), the spectra of
AT2018cow started to show broad features in the wave-
length range 5900 – 6100 Å. To aid in line identification,
we calculated a series of model spectra using TARDIS,
a one-dimensional Monte Carlo radiative transfer code
(Kerzendorf & Sim 2014; Kerzendorf et al. 2018). The
features could be emission of He II \( \lambda 4686 \), He I \( \lambda 5015 \)
or He II \( \lambda 5005 \), He I \( \lambda 5876 \), and He I \( \lambda 6678 \), respectively
(see Figure 3) but the potential emission features appear
redshifted with respect to the rest position by \( \sim 3000 \)
kms. The identification of these features with He I
and He II but offset to the red was also suggested by
Benetti et al. (2018).

3. TEMPERATURE AND PHOTOSPHERIC
VELOCITY EVOLUTION

The initial temperature of AT2018cow was estimated
by modelling the spectral energy distribution as a black-
body to be 27000 ± 2000 K at \( t = 4.1 \) d (Figure 2). The
temperature then shows a progressive decline over the
next two weeks to \( \sim 15000 \) K.

Assuming homologous expansion and that AT2018cow
was spherical, the photospheric velocity, \( v_{ph} \), and
photospheric radius, \( R_{ph} \), were also estimated (Figure 2).
The velocity at \( t = 4.1 \) d is \( v_{ph} \sim 16000 \pm 2000 \) kms\(^{-1}\),
declining to \( \sim 3000 \) kms\(^{-1}\) in two weeks. Over the same
period, the photospheric radius stays relatively constant
at \( \sim 5 \times 10^{14} \) cm.

4. BOLOMETRIC LIGHT CURVE ANALYSIS

Figure 2 shows the pseudo-bolometric (henceforth
“bolometric”) light curve of AT2018cow. It was con-
structed using the UV to NIR photometry (UVONIR,
1850 – 23000 Å) and the method described in Prentice
et al. (2016). Spline fits to the light curves were used to
interpolate the fluxes on SWIFT observation dates.

AT2018cow reached a peak UVONIR luminosity, \( L_p \)
\( \approx 1.7 \times 10^{44} \) erg s\(^{-1}\) (\( M = -21.8 \) mag). Measurements
Figure 2. **Upper left panel:** The ATLAS, LT, GROND, and SWIFT light curves of AT2018cow. The observations are in the rest frame, with $t_{\text{exp}}$ estimated from the light curve models. The ASAS-SN non-detection (black down-arrow) is shown, along with the last ATLAS non-detections. **Upper right panel:** The UVONIR (black) and griz (grey) bolometric light curves of AT2018cow, the dotted line is the time of the ASAS-SN non-detection. Other luminous transients with short rise times are also shown: iPTF16asu (Whitesides et al. 2017), PS1-11bbq, PS1-bjp, PS1-11qr (Drout et al. 2014), and the kilonova AT2017gfo (Smartt et al. 2017). No K-corrections have been applied to the photometry. Magnetar model fits to AT2018cow are shown as a black/grey solid lines, while the best-fitting $^{56}$Ni-powered model is shown as a grey dashed line. Magenta lines along the bottom indicate the dates of spectral observations. **Lower left panel:** The effective temperature and velocity evolution of AT2018cow. **Lower right panel:** The photospheric radius as function of time.
Figure 3. Spectra of AT2018cow (LT, ACAM, SNIFS) to +24.1 d, all epochs are rest-frame time since detection with the first spectrum at approximately maximum light. The inset shows the host Ca II H&K lines at $z = 0.0139$ (green dashed line).
of the characteristic light-curve timescales using a spline fit to the data gives a rise time from $L_p/2$ to $L_p$ of $t_{-1/2}$ < 1.7 d and an equivalent decay time after peak of $t_{+1/2}$ = 2.5 ± 0.5 d. Constraints from the photometric non-detections give a limit on the rise time of < 3.3 d to increase >5 mag.

4.1. Model fits to the bolometric light curves

The best-fitting $^{56}$Ni-powered light curve model (Arnett 1982; Valenti et al. 2008) has a $^{56}$Ni mass of $\approx 3$ M$_\odot$ and 0.05 – 0.3 M$_\odot$ of ejecta (for realistic ejecta velocities), which is unphysical. This model fits the peak luminosity and the rise, but not the decay (Figure 2), and no model fits all three.

We also investigated powering of AT2018cow by the highly-magnetized rapidly rotating neutron star (magnetar) models of Kasen & Bildsten (2010) as formulated in Inserra et al. (2013). For our model, we assumed spherical symmetry and 100% efficiency in thermalizing the spin-down energy. The best fitting model (Figure 2) has a spin period, $P \approx 11$ ms, a magnetic field strength, $B \approx 2.0 \times 10^{15}$ G, an explosion time, $t_{\text{exp}} \approx 1.1$ d before the ATLAS discovery, and a rise time to maximum light of $t_{\text{rise}} \approx 2.5$ d. The model fit to the griz light curve gives similar timescales but with $P \approx 25$ ms and $B \approx 3.5 \times 10^{15}$ G.

Using $t_{\text{rise}}$, and assuming an opacity of 0.1 – 0.2 cm$^2$ g$^{-1}$ and a kinetic energy in the range, $10^{51} < E_k < 10^{52}$ erg, we estimated a ejecta mass, $M_{ej} = 0.1 - 0.4$ M$_\odot$ for the magnetar model. This lies in between the $M_{ej}$ of the kilonova, AT2017gfo ($M_{ej} = 0.04 \pm 0.01$ M$_\odot$; Smartt et al. 2017; Drout et al. 2017) and low-mass stripped-envelope core-collapse events such as SN 1994I ($M_{ej} \sim 1$ M$_\odot$; Nomoto et al. 1994).

Late-time accretion onto a central compact object is predicted to roughly follow a $t^{-5/3}$ decay law (e.g., Chevalier 1989), which is similar to the $t^{-2}$ used in the magnetar model. Therefore, a fallback accretion scenario (Dexter & Kasen 2013) for AT2018cow predicts a similar $M_{ej}$.

5. DISCUSSION AND CONCLUSIONS

The combination of its high peak luminosity ($\approx 3.7 \times 10^{44}$ erg s$^{-1}$), fast rise time (>5 mag in 3.3 d), high peak blackbody temperature ($\approx 27000$ K), low ejecta mass (0.1 – 0.4 M$_\odot$), and relatively featureless and non-evolving spectra make AT2018cow very unusual. Some analogues at higher redshift may exist (Drout et al. 2014; Pursiainen et al. 2018), but discovery of events like AT2018cow are unprecedented in the local Universe.

A key result of our analysis is that a magnetar or accretion model requires a low ejecta mass of $\sim 0.1 - 0.4$ M$_\odot$, which is between that of a low-mass core-collapse event and the kilonova, AT2017gfo.

From our spectral analysis, we tentatively identify emission lines of He I. The peaks of the emission features are not quite aligned with the rest frame He I wavelengths. They are redshifted, suggestive of a large bulk velocity for the He-rich material. The presence of He is difficult to reconcile with either magnetar or accretion models since such a progenitor should have previously lost all its He.

Models such as shock-breakout or recombination in an extended envelope that have been put forward for other fast and luminous events (e.g., Drout et al. 2014). The shock breakout of SN 1993J was nearly two magnitudes fainter than AT2018cow and required a radius of $4 \times 10^{13}$ cm, already close to the limit for observed red supergiants (from calculations of Woosley et al. 1994). Therefore, an unfeasibly large and extended envelope would be required to power the light curve of AT2018cow via shock breakout. No signs of narrow line emission consistent with interaction with H/He-rich material is seen for AT2018cow, making a shock breaking out of circumstellar material such as in Ofek et al. (2010) unlikely.

A number of models have been put forward for the special case of the formation of a magnetar in a binary neutron star merger (Gao et al. 2013; Yu et al. 2013; Metzger & Piro 2014). These magnetar models predict transients that are more luminous and slower evolving than kilonovae (that would occur in addition to the kilonova event). In particular, the $M_{ej} = 0.1$ M$_\odot$ model with a magnetic field of $10^{15}$ G of Metzger & Piro (2014) predicts a UV/optical transient with a similar peak luminosity, decline rate, and effective temperature to that of AT2018cow. Although published models are not a perfect match, better fits may be possible by tuning model parameters. This model also predicts non-thermal X-ray emission on a similar timescale to the UV/optical emission.

Multiple X-ray (e.g., Rivera Sandoval et al. 2018) and radio/sub-millimeter (e.g., de Ugarte Postigo et al. 2018) detections have been made of AT2018cow. Further modelling and observations across the full electromagnetic spectrum will hopefully allow the origin of this unusual transient to be determined.

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**Facilities:** LT (IO:O, SPRAT), ATLAS

Table 1. UVONIR photometry of AT2018cow.

| MJD  | Phase | m    | δm  | Filter | Telescope |
|------|-------|------|-----|--------|-----------|
| 58279.50 | −5.6 | > 20.4 | c   | ATLAS  |
| 58281.48 | −3.9 | > 20.2 | o   | ATLAS  |
| 58284.13 | −1.3 | > 18.9 | g   | ASASSN |
| 58285.44 | 0.0  | 14.7  | 0.1 | ATLAS  |
| 58287.15 | 1.6  | 13.40 | 0.05 | GROND |
| 58287.15 | 1.6  | 13.8  | 0.1  | GROND  |
| 58287.15 | 1.6  | 14.1  | 0.1  | GROND  |
| 58287.15 | 1.6  | 14.32 | 0.05 | GROND  |
| 58287.15 | 1.6  | 14.71 | 0.07 | GROND  |
| 58287.15 | 1.6  | 15.10 | 0.08 | GROND  |
| 58287.15 | 1.6  | 15.3  | 0.1  | GROND  |
| 58287.44 | 1.9  | 13.60 | 0.01 | ATLAS  |
| 58288.20 | 2.7  | 13.65 | 0.05 | GROND  |
| 58288.20 | 2.7  | 14.1  | 0.1  | GROND  |
| 58288.20 | 2.7  | 14.4  | 0.1  | GROND  |
| 58288.20 | 2.7  | 14.67 | 0.05 | GROND  |
| 58288.20 | 2.7  | 15.04 | 0.07 | GROND  |
| 58288.20 | 2.7  | 15.43 | 0.07 | GROND  |
| 58288.20 | 2.7  | 15.6  | 0.1  | GROND  |
| 58288.50 | 3.0  | 13.25 | 0.03 | UVOT   |
| 58288.50 | 3.0  | 13.32 | 0.04 | UVOT   |
| 58288.85 | 3.0  | 13.31 | 0.04 | UVOT   |
| 58288.85 | 3.0  | 13.56 | 0.06 | Swift-u |
| 58288.50 | 3.0  | 13.77 | 0.06 | Swift-b |
| 58288.50 | 3.0  | 13.88 | 0.07 | Swift-v |
| 58288.98 | 3.4  | 13.84 | 0.08 | LT     |
| 58288.98 | 3.4  | 14.12 | 0.06 | LT     |
| 58288.98 | 3.4  | 14.32 | 0.03 | LT     |
| 58288.98 | 3.4  | 14.76 | 0.03 | LT     |
| 5829.17  | 3.6  | 14.06 | 0.05 | GROND  |
| 5829.17  | 3.6  | 14.3  | 0.1  | GROND  |
| 5829.17  | 3.6  | 14.8  | 0.1  | GROND  |
| 5829.17  | 3.6  | 15.01 | 0.05 | GROND  |
| 5829.17  | 3.6  | 15.34 | 0.07 | GROND  |
| 5829.17  | 3.6  | 15.81 | 0.08 | GROND  |
| 5829.17  | 3.6  | 15.9  | 0.1  | GROND  |
| 5829.22  | 3.7  | 13.57 | 0.06 | UVOT   |
| UTCT     | Obs.     | u     | g     | r     | i     | z     |
|----------|----------|-------|-------|-------|-------|-------|
| 58289.22 | 3.7      | 13.60 | 0.07  | uvm2  | UVOT  |
| 58289.22 | 3.7      | 13.55 | 0.07  | uvw1  | UVOT  |
| 58289.22 | 3.7      | 13.87 | 0.07  | Swift-u | UVOT |
| 58289.22 | 3.7      | 14.08 | 0.07  | Swift-b | UVOT |
| 58289.22 | 3.7      | 14.14 | 0.07  | Swift-v | UVOT |
| 58290.02 | 4.5      | 14.29 | 0.03  | u     | LT    |
| 58290.02 | 4.5      | 14.58 | 0.06  | g     | LT    |
| 58290.02 | 4.5      | 14.63 | 0.03  | r     | LT    |
| 58290.02 | 4.5      | 14.97 | 0.03  | i     | LT    |
| 58290.02 | 4.5      | 15.09 | 0.05  | z     | LT    |
| 58290.08 | 4.5      | 14.45 | 0.05  | g'    | GROND |
| 58290.08 | 4.5      | 14.6  | 0.1   | r'    | GROND |
| 58290.08 | 4.5      | 14.9  | 0.1   | i'    | GROND |
| 58290.08 | 4.5      | 15.08 | 0.05  | z'    | GROND |
| 58290.08 | 4.5      | 15.33 | 0.08  | J     | GROND |
| 58290.08 | 4.5      | 15.57 | 0.08  | H     | GROND |
| 58290.08 | 4.5      | 15.7  | 0.1   | K     | GROND |
| 58290.50 | 4.9      | 14.22 | 0.09  | uvw2  | UVOT  |
| 58290.50 | 4.9      | 14.2  | 0.1   | uvm2  | UVOT  |
| 58290.50 | 4.9      | 14.16 | 0.07  | uvw1  | UVOT  |
| 58290.50 | 4.9      | 14.42 | 0.07  | Swift-u | UVOT |
| 58290.50 | 4.9      | 14.75 | 0.07  | Swift-b | UVOT |
| 58290.50 | 4.9      | 14.67 | 0.07  | Swift-v | UVOT |
| 58290.97 | 5.4      | 14.65 | 0.03  | u     | LT    |
| 58290.97 | 5.4      | 15.02 | 0.06  | g     | LT    |
| 58290.97 | 5.4      | 15.06 | 0.03  | r     | LT    |
| 58290.97 | 5.4      | 15.33 | 0.03  | i     | LT    |
| 58290.97 | 5.4      | 15.49 | 0.03  | z     | LT    |
| 58291.20 | 5.6      | 14.92 | 0.05  | g'    | GROND |
| 58291.20 | 5.6      | 15.1  | 0.1   | r'    | GROND |
| 58291.20 | 5.6      | 15.3  | 0.1   | i'    | GROND |
| 58291.20 | 5.6      | 15.49 | 0.05  | z'    | GROND |
| 58291.20 | 5.6      | 15.86 | 0.08  | J     | GROND |
| 58291.20 | 5.6      | 16.15 | 0.08  | H     | GROND |
| 58291.20 | 5.6      | 16.1  | 0.1   | K     | GROND |
| 58291.43 | 5.9      | 15.34 | 0.03  | o     | ATLAS |
| 58291.69 | 6.1      | 14.59 | 0.06  | uvw2  | UVOT  |
| 58291.69 | 6.1      | 14.57 | 0.07  | uvm2  | UVOT  |
| 58291.69 | 6.1      | 14.4  | 0.1   | uvw1  | UVOT  |
| 58291.69 | 6.1      | 14.70 | 0.07  | Swift-u | UVOT |
| 58291.69 | 6.1      | 15.02 | 0.08  | Swift-b | UVOT |
| 58291.69 | 6.1      | 14.96 | 0.08  | Swift-v | UVOT |
| 58291.98 | 6.4      | 14.85 | 0.07  | u     | LT    |
| 58291.98 | 6.4      | 15.24 | 0.06  | g     | LT    |
| 58291.98 | 6.4      | 15.32 | 0.03  | r     | LT    |
| 58291.98 | 6.4      | 15.51 | 0.03  | i     | LT    |
| 58291.98 | 6.4      | 15.62 | 0.03  | z     | LT    |
| 58292.09 | 6.5      | 14.8  | 0.1   | uvw2  | UVOT  |
| 58292.09 | 6.5      | 14.90 | 0.07  | uvm2  | UVOT  |
| Date (MJD) | Mag. | Filter | $\Delta mag$ | Source |
|-----------|------|--------|--------------|--------|
| 58292.09  | 6.5  | 14.76  | 0.08         | $uvw1$ UVOT |
| 58292.09  | 6.5  | 14.81  | 0.09         | Swift- $u$ UVOT |
| 58292.09  | 6.5  | 15.12  | 0.08         | Swift- $b$ UVOT |
| 58292.09  | 6.5  | 15.10  | 0.08         | Swift- $v$ UVOT |
| 58292.10  | 6.5  | 15.07  | 0.05         | $g'$ GROND |
| 58292.10  | 6.5  | 15.2   | 0.1          | $r'$ GROND |
| 58292.10  | 6.5  | 15.4   | 0.1          | $i'$ GROND |
| 58292.10  | 6.5  | 15.54  | 0.05         | $z'$ GROND |
| 58292.10  | 6.5  | 15.97  | 0.08         | $J$ GROND |
| 58292.10  | 6.5  | 16.30  | 0.09         | $H$ GROND |
| 58292.10  | 6.5  | 16.2   | 0.1          | $K$ GROND |
| 58292.96  | 7.4  | 15.0   | 0.1          | $u$ LT |
| 58292.96  | 7.4  | 15.43  | 0.06         | $g$ LT |
| 58292.96  | 7.4  | 15.52  | 0.03         | $r$ LT |
| 58292.96  | 7.4  | 15.66  | 0.03         | $i$ LT |
| 58292.96  | 7.4  | 15.76  | 0.04         | $z$ LT |
| 58293.12  | 7.5  | 15.28  | 0.05         | $g'$ GROND |
| 58293.12  | 7.5  | 15.5   | 0.1          | $r'$ GROND |
| 58293.12  | 7.5  | 15.6   | 0.1          | $i'$ GROND |
| 58293.12  | 7.5  | 15.74  | 0.05         | $z'$ GROND |
| 58293.12  | 7.5  | 16.12  | 0.08         | $J$ GROND |
| 58293.12  | 7.5  | 16.37  | 0.08         | $H$ GROND |
| 58293.12  | 7.5  | 16.3   | 0.1          | $K$ GROND |
| 58293.43  | 7.8  | 15.67  | 0.01         | $o$ ATLAS |
| 58293.97  | 8.4  | 15.3   | 0.07         | $u$ LT |
| 58293.97  | 8.4  | 15.65  | 0.06         | $g$ LT |
| 58293.97  | 8.4  | 15.69  | 0.03         | $r$ LT |
| 58293.97  | 8.4  | 15.82  | 0.03         | $i$ LT |
| 58293.97  | 8.4  | 15.86  | 0.04         | $z$ LT |
| 58294.13  | 8.5  | 15.45  | 0.05         | $g'$ GROND |
| 58294.13  | 8.5  | 15.6   | 0.1          | $r'$ GROND |
| 58294.13  | 8.5  | 15.7   | 0.1          | $i'$ GROND |
| 58294.13  | 8.5  | 15.77  | 0.05         | $z'$ GROND |
| 58294.13  | 8.5  | 16.0   | 0.1          | $J$ GROND |
| 58294.13  | 8.5  | 16.15  | 0.09         | $H$ GROND |
| 58294.13  | 8.5  | 16.0   | 0.1          | $K$ GROND |
| 58294.55  | 8.9  | 15.6   | 0.1          | $uvw2$ UVOT |
| 58294.55  | 8.9  | 15.4   | 0.1          | $uvm2$ UVOT |
| 58294.55  | 8.9  | 15.41  | 0.07         | $uvw1$ UVOT |
| 58294.55  | 8.9  | 15.44  | 0.08         | Swift- $u$ UVOT |
| 58294.55  | 8.9  | 15.59  | 0.08         | Swift- $b$ UVOT |
| 58294.55  | 8.9  | 15.57  | 0.09         | Swift- $v$ UVOT |
| 58294.95  | 9.3  | 15.57  | 0.08         | $u$ LT |
| 58294.95  | 9.3  | 15.90  | 0.06         | $g$ LT |
| 58294.95  | 9.3  | 15.97  | 0.03         | $r$ LT |
| 58294.95  | 9.3  | 16.07  | 0.03         | $i$ LT |
| 58294.95  | 9.3  | 16.12  | 0.04         | $z$ LT |
| 58295.10  | 9.5  | 15.75  | 0.05         | $g'$ GROND |
| 58295.10  | 9.5  | 15.9   | 0.1          | $r'$ GROND |
| 58295.10  | 9.5  | 16.1   | 0.1          | $i'$ GROND |
| Date       | H       | i       | r       | i'      |
|------------|---------|---------|---------|---------|
| 58295.10   | 9.5     | 16.12   | 0.05    | z'      |
| 58295.10   | 9.5     | 16.4    | 0.1     | J       |
| 58295.10   | 9.5     | 16.66   | 0.09    | H       |
| 58295.10   | 9.5     | 16.6    | 0.1     | K       |
| 58295.55   | 9.9     | 15.8    | 0.1     | uvw2    |
| 58295.55   | 9.9     | 15.61   | 0.08    | uwm2    |
| 58295.55   | 9.9     | 15.5    | 0.1     | uvw1    |
| 58295.55   | 9.9     | 15.58   | 0.08    | Swift-u |
| 58295.55   | 9.9     | 15.59   | 0.09    | Swift-b |
| 58295.55   | 9.9     | 15.6    | 0.1     | Swift-v |
| 58295.95   | 10.3    | 15.7    | 0.7     | u       |
| 58295.95   | 10.3    | 16.06   | 0.06    | g       |
| 58295.95   | 10.3    | 16.14   | 0.03    | r       |
| 58295.95   | 10.3    | 16.23   | 0.03    | i       |
| 58295.95   | 10.3    | 16.24   | 0.03    | z       |
| 58296.15   | 10.5    | 15.92   | 0.05    | g'      |
| 58296.15   | 10.5    | 16.1    | 0.1     | r'      |
| 58296.15   | 10.5    | 16.2    | 0.1     | i'      |
| 58296.15   | 10.5    | 16.27   | 0.05    | z'      |
| 58296.15   | 10.5    | 16.5    | 0.1     | J       |
| 58296.15   | 10.5    | 16.7    | 0.09    | H       |
| 58296.15   | 10.5    | 16.6    | 0.1     | K       |
| 58296.55   | 10.9    | 16.0    | 0.1     | uvw2    |
| 58296.55   | 10.9    | 15.88   | 0.08    | uwm2    |
| 58296.55   | 10.9    | 15.75   | 0.08    | uvw1    |
| 58296.55   | 10.9    | 15.7    | 0.1     | Swift-u |
| 58296.55   | 10.9    | 15.78   | 0.08    | Swift-b |
| 58296.55   | 10.9    | 15.75   | 0.09    | Swift-v |
| 58296.98   | 11.3    | 15.85   | 0.08    | u       |
| 58296.98   | 11.3    | 16.19   | 0.06    | g       |
| 58296.98   | 11.3    | 16.28   | 0.03    | r       |
| 58296.98   | 11.3    | 16.36   | 0.04    | i       |
| 58296.98   | 11.3    | 16.35   | 0.06    | z       |
| 58297.09   | 11.4    | 16.00   | 0.05    | g'      |
| 58297.09   | 11.4    | 16.2    | 0.1     | r'      |
| 58297.09   | 11.4    | 16.3    | 0.1     | i'      |
| 58297.09   | 11.4    | 16.34   | 0.05    | z'      |
| 58297.09   | 11.4    | 16.4    | 0.1     | J       |
| 58297.09   | 11.4    | 16.67   | 0.09    | H       |
| 58297.09   | 11.4    | 16.7    | 0.1     | K       |
| 58297.43   | 11.8    | 16.5    | 0.2     | o       |
| 58297.53   | 11.9    | 16.1    | 0.1     | uvw2    |
| 58297.79   | 12.1    | 16.1    | 0.1     | uvw2    |
| 58297.79   | 12.1    | 16.0    | 0.1     | uwm2    |
| 58297.79   | 12.1    | 15.8    | 0.1     | uvw1    |
| 58297.97   | 12.3    | 15.96   | 0.03    | u       |
| 58297.97   | 12.3    | 16.27   | 0.06    | g       |
| 58297.97   | 12.3    | 16.38   | 0.03    | r       |
| 58297.97   | 12.3    | 16.44   | 0.04    | i       |
| 58297.97   | 12.3    | 16.41   | 0.04    | z       |
| Date      | RA   | Dec  | Mag  | Type  | Filter | Instrument | Date      | RA   | Dec  | Mag  | Type  | Filter | Instrument |
|-----------|------|------|------|-------|--------|------------|-----------|------|------|------|-------|--------|------------|
| 58298.18  | 12.5 | 16.09| 0.05 | 1.0   | g'     | GROND     | 58298.18  | 12.5 | 16.3 | 0.1 | r'    | GROND  |
| 58298.18  | 12.5 | 16.4 | 0.1  | 1.0   | i'     | GROND     | 58298.18  | 12.5 | 16.42| 0.05| z'    | GROND  |
| 58298.18  | 12.5 | 16.3 | 0.1  | 1.0   | J      | GROND     | 58298.18  | 12.5 | 16.63| 0.09| H     | GROND  |
| 58298.18  | 12.5 | 16.3 | 0.1  | 1.0   | K      | GROND     | 58299.40  | 14.3 | 16.2 | 0.1 | u     | LT     |
| 58299.40  | 14.3 | 16.49| 0.06 | 1.0   | v      | LT        | 58300.59  | 14.9 | 16.7 | 0.1 | u     | UVOT   |
| 58300.59  | 14.9 | 16.35| 0.03 | 1.0   | v      | LT        | 58300.98  | 15.3 | 16.62| 0.06| g     | LT     |
| 58300.98  | 15.3 | 16.77| 0.03 | 1.0   | r     | LT        | 58300.98  | 15.3 | 16.83| 0.03| i     | LT     |
| 58301.97  | 16.3 | 16.82| 0.07 | 1.0   | g     | LT        | 58301.97  | 16.3 | 16.95| 0.05| r     | LT     |
| Time (s) | A | B | C | D |
|---------|---|---|---|---|
| 58301.97 | 16.3 | 16.99 | 0.06 | i |
| 58301.97 | 16.3 | 16.89 | 0.05 | z |
| 58302.07 | 16.4 | 17.01 | 0.07 | uvw2 |
| 58302.07 | 16.4 | 16.87 | 0.09 | uvw2 |
| 58302.07 | 16.4 | 16.64 | 0.09 | uvw1 |
| 58302.07 | 16.4 | 16.35 | 0.09 | Swift-u |
| 58302.07 | 16.4 | 16.19 | 0.09 | Swift-b |
| 58302.07 | 16.4 | 16.2 | 0.1 | Swift-v |

\(^a\)Rest-frame with respect to first observation

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