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THE LIGHT CURVE OF THE MACRONOVA ASSOCIATED WITH THE LONG–SHORT BURST GRB 060614

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ABSTRACT

The *Swift*-detected GRB 060614 was a unique burst that straddles an imaginary divide between long- and short-duration gamma-ray bursts (GRBs), and its physical origin has been heavily debated over the years. Recently, a distinct, very soft F814W-band excess at $t \sim 13.6$ days after the burst was identified in a joint-analysis of VLT and *Hubble Space Telescope* optical afterglow data of GRB 060614, which has been interpreted as evidence for an accompanying macronova (also called a kilonova). Under the assumption that the afterglow data in the time interval of 1.7–3.0 days after the burst are due to external FS emission, when this assumption is extrapolated to later times it is found that there is an excess of flux in several multi-band photometric observations. This component emerges at ~4 days after the burst, and it may represent the first time that a multi-epoch/band light curve of a macronova has been obtained. The macronova associated with GRB 060614 peaked at $t \lesssim 4$ days after the burst, which is significantly earlier than that observed for a supernova associated with a long-duration GRB. Due to the limited data, no strong evidence for a temperature evolution is found. We derive a conservative estimate of the macronova rate of $\sim 16.3^{+16.3}_{-8.2}\ \mathrm{Gpc^{-3}\ yr^{-1}}$, implying a promising prospect for detecting the gravitational wave radiation from compact-object mergers by upcoming Advanced LIGO/VIRGO/KAGRA detectors (i.e., the rate is $\mathcal{R}_{\rm GW} \sim 0.5^{+0.5}_{-0.25}(D/200\ \mathrm{Mpc})^3\ \mathrm{yr^{-1}}$).

Key words: binaries: general – gamma-ray burst: individual (GRB 060614) – radiation mechanisms: thermal – stars: neutron

1. INTRODUCTION

It is widely accepted that the merger of a binary compact-object system (either a neutron-star (NS) binary or a stellar-mass black hole (BH) and NS binary) produces the high-energy γ-ray emission in a short-duration gamma-ray burst (SGRB) event (Eichler et al. 1989; Narayan et al. 1992; Berger 2014). Indirect evidence for SGRBs originating from compact binaries (Gehrels et al. 2005; Fong et al. 2010; Leibler & Berger 2010; Fong & Berger 2013; Berger 2014) include the location of SGRBs in elliptical galaxies, no associated supernova (SN), large galaxy offsets (>100 kpc) that match population synthesis predictions for compact binaries, and weak spatial correlation of SGRBs and regions of star formation within their host galaxies (when the hosts can be unambiguously identified).

A "smoking-gun" signature for the compact-binary origin of an SGRB would be the detection of the so-called Li-Paczynski macronova (also called a kilonova), which is a near-infrared/optical transient powered by the radioactive decay of *r*-process material synthesized in the ejecta that is launched during the merger event (e.g., Li & Paczyński 1998; Kulkarni 2005; Rosswog 2005; Metzger et al. 2010; Korobkin et al. 2012; Barnes & Kasen 2013; Kasen et al. 2013; Tanaka & Hotokezaka 2013; Grossman et al. 2014; Tanaka et al. 2014; Kisaka et al. 2015a, 2015b; Lippuner & Roberts 2015). Macronovae are expected to peak in infrared bands, and they display very soft spectra. As such, macronova signals are very hard to detect. A breakthrough was made in 2013 June. In the late afterglow of the canonical SGRB 130603B ($z = 0.356$), an infrared transient was interpreted as a macronova produced during a compact-binary merger (Berger et al. 2013; Hotokezaka et al. 2013; Tanvir et al. 2013; Piran et al. 2014). Very recently, a significant F814W-band excess component was reported in a re-analysis of the late time optical afterglow data (Yang et al. 2015; Y15 hereafter) of the peculiar event GRB 060614 which shares some properties of both long- and short-duration gamma-ray burts (Della Valle et al. 2006; Fynbo et al. 2006; Gal-Yam et al. 2006; Gehrels et al. 2006; Zhang et al. 2007). The photometric spectral energy distribution (SED) of the excess component is so soft (the effective temperature is below 3000 K) that a very weak SN origin has been strongly disfavored. Instead, the excess flux can be interpreted as a macronova powered by the merger of a stellar-mass BH with an NS (Y15).

To date, the published literature regarding photometric evidence of macronovae associated with SGRB 130603B and long–short burst GRB 060614 are based on only a single data point in each event.[5] To better reveal the physical processes giving rise to the macronova emission, multi-band photometric (and ideally spectroscopic) observations of the transient are needed in order to compare observations with theoretical predictions (e.g., Barnes & Kasen 2013; Hotokezaka et al. 2013; Tanaka & Hotokezaka 2013; Grossman et al. 2014; Tanaka et al. 2014). We therefore revisited the extensive data set of GRB 060614 obtained with the Very Large Telescope (VLT) and *Hubble Space Telescope* (*HST*) to produce multi-band light curves and SEDs, and we use this information to provide evidence for and constrain the nature of the accompanying macronova.

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[5] In Figure 1 of Y15, at $t \sim 7.8$ days after the burst there was an *I*-band data point that was in excess of the extrapolated power-law decline of the hypothesized forward shock (FS) emission. However, its significance was below 3σ.

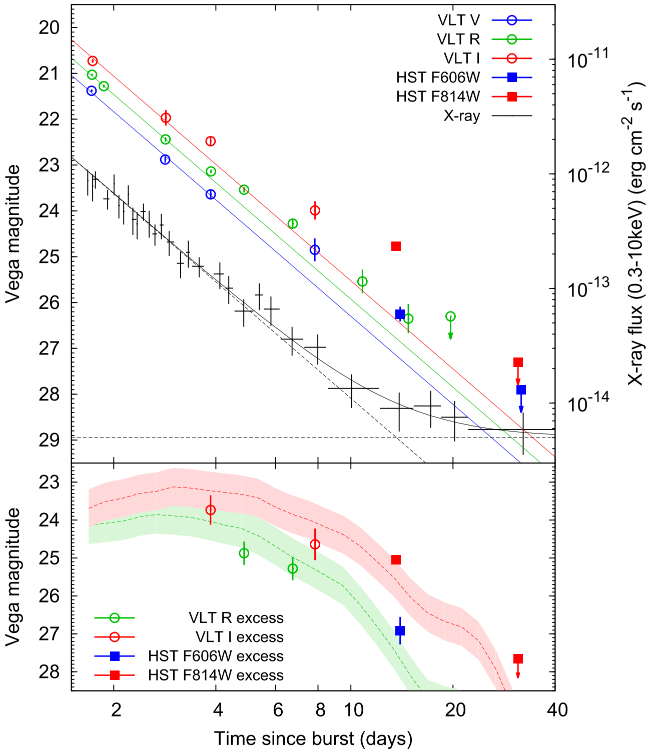

Figure 1. Observed light curves of the macronova associated with GRB 060614. Top: the data points are adopted from Y15 but only the VLT data in the time interval of 1.7–3.0 days are assumed to arise solely from FS emission; the solid lines represent the fit ($\propto t^{-2.55}$). The simultaneous X-ray emission, retrieved from the UK *Swift* Science Data Centre (Evans et al. 2009), can be fitted by $t^{-2.55}$ plus a constant X-ray flux of $(8 \pm 4) \times 10^{-15}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ was obtained by Mangano et al. (2007) and was interpreted as the emission from a possible active galactic nucleus, or it was simply a statistical fluctuation because of the low measured flux that was very close to the detection threshold of *Swift* XRT. Simultaneous with the very late/weak "plateau-like" X-ray emission, the HST F814W-band flux drops as $t^{-3.2}$, ruling out a possible energy injection mechanism. Bottom: significant excess appears at late times. Note that the data are not corrected for any extinction and only "macronova" emission points with a significance above 2σ were kept. The dashed lines, adopted from Y15, are macronova model light curves generated from a numerical simulation for the ejecta from a BH–NS merger, with a velocity of $\sim$0.2c and a mass $M_{\rm ej} \sim 0.1 M_\odot$ (Tanaka et al. 2014). The green and red lines are in R and I bands, and shadows represent a possible uncertainty of 0.5 mag (K. Hotokezaka 2015, private communication). The macronova model is in agreement with the observed data, including those with large uncertainties (i.e., significance below 2σ, see Table 1).

This work is structured as follows: in Section 2 we first review the basic assumptions made in Y15. Next, we discuss the necessity/feasibility of relaxing these assumptions and then extract the light curve of the associated macronova. The rate of macronova/compact-object mergers is estimated in Section 3, and our results and discussion are presented in Section 4.

2. EXTRACTING THE LIGHT CURVE OF MACRONOVA ASSOCIATED WITH GRB 060614

To robustly establish the existence of a distinct HST F814W-band excess in the late afterglow of GRB 060614, Y15 assumed that all of the VLT data were due to the FS and subsequently fitted the *VRI* data at $t > 1.7$ days with the same decline rate. In such an approach, only one F814W-band point at about 13.6 days was found to be more than 3σ in excess of the fitted FS emission. However, the fitted residuals in Figure 1 of Y15 display an interesting general trend: the earlier data ($t < 4$ days) were usually negative (with respect to the FS afterglow model), while the later data were positive, indicating that the intrinsic FS emission decline was likely steeper than that assumed in their model, and there was likely to be an excess of emission at times earlier than 13.6 days. On the other hand, in numerical simulations, macronova *optical* emission usually peaks in a few days to a week (rest frame) after the merger event, and its subsequent contribution to the afterglow emission can be non-negligible (e.g., Barnes & Kasen 2013; Tanaka & Hotokezaka 2013; Tanaka et al. 2014). After having solidly established the existence of an excess of flux in the analysis performed by Y15, we sought to improve the analysis by considering a possible time evolution of the macronova component and modeling the entire afterglow data set accordingly.

GRB afterglows are expected to be powered by FSs that produce synchrotron emission. Such GRBs have a power-law like behavior in both time and frequency where the temporal and energy spectral indices, α and β, respectively, are defined by $f_\nu \propto t^{-\alpha}\nu^{-\beta}$, where t is the time since the GRB was first detected by a satellite (e.g., Piran 2004; Kumar & Zhang 2015). For SGRBs, the afterglow emission emitted after several hours should consist of radiation coming from both the FS and the associated macronova. Hence a macronova light curve can, in principle, be "self-consistently" obtained through a joint fit of the observational data. A key outstanding problem is that current theoretical macronova calculations still suffer from significant uncertainties. For example, the role of radioactive heating due to the fission of heavy r-process nuclei to the energy deposition rate at, for example, $t \sim 10$ days after the merger, is still poorly understood (e.g., Korobkin et al. 2012; Wanajo et al. 2014; K. Hotokezaka 2015, private communication). Moreover, the poorly constrained electron fraction ($Y_{\rm e}$), the escape velocity distribution and the anisotropy of the outflow play additional roles in shaping the macronova emission (Tanaka et al. 2014; Lippuner & Roberts 2015); all of these are caveats that should be considered when interpreting our results.

In this work we extracted the possible macronova emission by decomposing the FS emission from the observational data. A reliable estimate of the FS emission is very crucial, so the following facts were taken into account: (i) there was a jet break around 1.4 days (Della Valle et al. 2006; Mangano et al. 2007; Xu et al. 2009), hence only data after this time need to be considered, (ii) at $t \sim 1.7$–1.9 days after the burst, the optical to X-ray spectrum is well described by a single power-law (Della Valle et al. 2006; Mangano et al. 2007; Xu et al. 2009), suggesting that any macronova contribution to the observed flux is negligible, and (iii) in the interval of 1.7–3.0 days after the burst, there were two measurements in VLT *VI* bands and three measurements in the VLT R band, allowing us to obtain a relatively reliable estimate of the FS emission decline. Therefore, in this work we adopt the VLT and *HST* observational data reduced in Y15, but we assume that only the VLT data in the interval of 1.7–3.0 days are due solely to FS emission, and we use these data to determine the single power-law decline of the afterglow.

The observed magnitudes were first corrected to the magnitudes in the R band, assuming a Galactic extinction of $A_V = 0.07$ mag (Schlegel et al. 1998; Schlafly & Finkbeiner 2011). The extinction of the host galaxy is SMC-like, $A_V = 0.05$ mag, and the intrinsic afterglow spectrum is well

Table 1
The Macronova Component of GRB 060614

Time from GRB (days)	Filter	Magnitude[a] (Vega)
7.828	VLT *V*	(25.6 ± 0.6)
3.869	VLT *R*	(25.3 ± 0.6)
4.844	VLT *R*	24.9 ± 0.3
6.741	VLT *R*	25.3 ± 0.3
10.814	VLT *R*	(26.5 ± 0.8)
14.773	VLT *R*	(27.2 ± 1.0)
3.858	VLT *I*	23.7 ± 0.4
7.841	VLT *I*	24.6 ± 0.4
13.970	HST F606W	26.9 ± 0.4
13.571	HST F814W	25.05 ± 0.12

Note.
[a] The magnitudes of the extracted macronova component. The observations with errors larger than 0.5 mag have been bracketed.

described by a single power-law with $\beta = 0.81 \pm 0.08$, as based on the optical and UV data at 150 ks fitted by Mangano et al. (2007) and confirmed by Xu et al. (2009). The fit to the VLT data collected in the time interval of 1.7–3.0 days yields $\alpha = 2.55 \pm 0.09$. This is steeper than the decay index of $\alpha = 2.30 \pm 0.03$ obtained in Y15 by assuming all VLT data were FS emission. Such a difference is reasonable/expected since the "underlying" macronova emission contributes to observations at later epochs, thus causing the LCs to appear to decay at a slower rate. In the slow cooling of a jetted outflow with significant sideways expansion, when the observational frequency is between the so-called typical synchrotron radiation frequency $\nu_{\rm m}$ and the cooling frequency $\nu_{\rm c}$, the decline and spectral indices are expected to be $\alpha = p$ (after the jet break; Sari et al. 1999) and $\beta = (p - 1)/2$ (Piran 2004; Kumar & Zhang 2015). Interestingly the observed $\beta = 0.81 \pm 0.08$ and our inferred $\alpha = 2.55 \pm 0.09$ are in good agreement with the standard afterglow model (i.e., they both predict an electron index of $p \approx 2.6$).

When we subtracted this FS component from the observational data we found a significant excess in multi-wavelength bands at $t > 3$ days, which may constitute the first multi-epoch/band light curve of a macronova ever recorded. The results are shown in Table 1 and Figure 1, where the errors include the uncertainties of the observed magnitudes and the FS model uncertainties. Although the data set is still relatively sparse, there is an indication that the macronova emission likely peaked at $t \lesssim 4$ days after the merger event,[6] which is consistent with current numerical simulations (e.g., Kasen et al. 2013; Tanaka & Hotokezaka 2013; Tanaka et al. 2014). In comparison, among GRB-associated SNe, SN 2010bh had the most rapid rise to maximum brightness, peaking at $t = 8.5 \pm 1.1$ days after GRB 100316D (Cano et al. 2011; Bufano et al. 2012; Olivares et al. 2012), which is significantly later than that found here. Therefore, in addition to the remarkably soft spectrum at about 13.6 days after the burst noticed by Y15, the rather early peak of the excess components found in this work strongly disfavors an SN interpretation. In the NS–NS merger scenario, Metzger & Fernández (2014) found that some regions of the outflow may be Lanthanide-free, and such material will become optically thin within a few days after the merger, giving rise to optical/UV emission that lasts for a day or so. Such a scenario can, at least in part, explain the early peak in the macronova observed here. A successful interpretation of the very significant F814W-band excess emission at $t \sim 13.6$ days is, however, a challenge for theoretical NS–NS merger models.

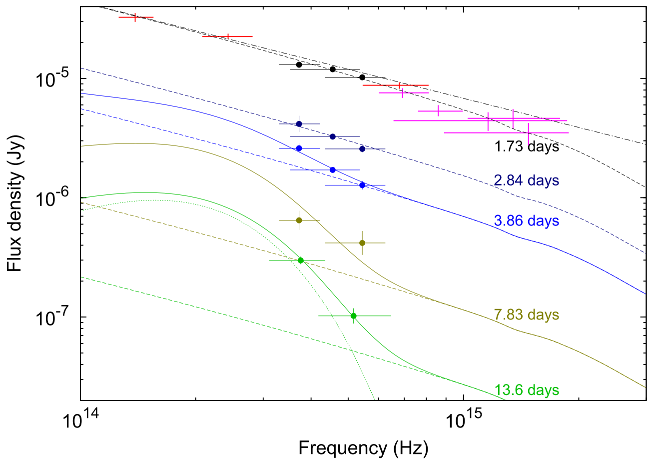

Figure 2. Observed SED evolution of GRB 060614. From top to bottom are the SEDs at $t = (1.73,\ 2.84,\ 3.86,\ 7.83,\ 13.6)$ days, respectively. Solid circles are from Y15, red crosses are VLT data from Della Valle et al. (2006), and purple crosses are *Swift* UVOT data from Mangano et al. (2007); all data have not been corrected for extinction. In two early observations the SEDs can be fitted with a single power-law spectrum with extinction of the Galaxy and the host galaxy, where the dash–dot line is the intrinsic spectrum and dashed lines are extincted. The remaining three observations are fitted by a single power-law and a blackbody spectrum ($T = 2700$ K, dotted line) where extinction has been taken into account.

There are five epochs that consist of two or more filters, which we have combined into five SEDs, and these are displayed in Figure 2. An excess of flux (i.e., relative to a single power-law spectrum) is clearly visible in the three latter epochs. Blackbody spectra provide a reasonable fit to the observed SEDs (see Figure 2). At $t \sim 13.6$ days after the burst, the temperature is estimated to be 2700^{-500}_{+700} K. At other times, the temperatures are poorly constrained (i.e., <4200 K and 3100–19,000 K at 3.86 and 7.83 days, respectively). Due to the large errors, it is impossible to draw any conclusions regarding a possible temperature evolution.

As pointed out in Y15, the progenitor system was likely a BH–NS binary, as these types of mergers are expected to give rise to "bluer," longer, and brighter macronova emission than NS–NS mergers due to greater ejecta mass and a highly anisotropic distribution of the ejecta material (see Tanaka et al. 2014; Kyutoku et al. 2015 and the references therein). For GRB 060614, to account for the distinct F814W-band excess at $t \sim 13.6$ days, a simple estimate based on the generation of the macronova light curve in one BH–NS merger model presented in Tanaka et al. (2014) suggests that the ejected material from the merger was $\sim 0.1\ M_\odot$ and moved at a velocity $\sim 0.2c$. In this paper, the F814W-band excess is just a bit brighter and the parameters of the ejecta are likely similar to those in a previous estimate. The peak emission of VLT/*I*-band (*R*-band) excess is as bright as ~24th mag (~25th mag), in agreement with the

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[6] After extracting the possible macronova emission from the data, we find that the macronova was always much fainter than the afterglow between 1.7 and 3.0 days after the burst and its contribution was smaller than the afterglow uncertainties. Hence our assumption that in the time interval of 1.7–3.0 days the emission is due solely to FS is reasonable. However, due to the $t^{-2.55}$ decline of the FS emission and the shallow decay of the macronova, at $t \geqslant 4$ days the contribution of a macronova to the total flux cannot be ignored any longer.

merger macronova model (see Figure 1). A reliable interpretation of the macronova light curve, however, requires dedicated numerical simulation studies including a proper convolution of the produced complicated macronova spectra with the response function of the most widely used facilities in order to aid the comparison with actual data, which is beyond the scope of this work.

3. THE RATE OF THE MACRONOVA AND COMPACT-OBJECT MERGERS

So far, two macronovae have been observed at redshifts of $z = 0.356$ and $z = 0.125$ for GRB 130603B (Berger et al. 2013; Tanvir et al. 2013) and GRB 060614 (Y15), respectively. Both events were found to be collimated with a half-opening angle $\theta_{\rm j} \sim 0.1$ (e.g., Xu et al. 2009; Fan et al. 2013; Fong et al. 2014). For the macronovae at $z \geqslant 0.4$, *HST* observations are crucial to get the signal but *HST* observations of such "high"-z short GRBs were very rare (Berger 2014). The current sample can be taken as that recordable by *Swift*, an instrument with a field-of-view of 2 steradians, in the last 10 years for the events with $z \leqslant 0.4$. With these numbers in mind, we estimated the local macronova/compact-object merger rate to be

$$\mathcal{R}_{\rm macronova} \sim 16.3^{+16.3}_{-8.2}\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}\left(\theta_{\rm j}/0.1\right)^{-2}.$$

Note that this rate is corrected for beaming; as such, it is compatible with the un-beamed SGRB rate of $4 \pm 2\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$ (Wanderman & Piran 2015). For the upcoming Advanced LIGO/VIRGO/KAGRA detectors that will detect the gravitational wave radiation from compact-object mergers within a distance $D \sim 200$ Mpc (Aasi et al. 2013), the detection rate is expected to be

$$\mathcal{R}_{\rm GW} \sim 0.5^{+0.5}_{-0.25}(D/200\ {\rm Mpc})^3\ {\rm yr}^{-1}.$$

Bear in mind that such rates are (very) conservative since (1) macronova searches usually need *HST*-like detectors and not all SGRBs and long–short GRBs have been followed down to deep limits and (2) it is likely that just a fraction of compact-object mergers can produce GRBs. Hence, the above estimates are better taken as lower limits. We thus conclude that the prospect of detecting gravitational wave radiation from merger events in the near future is quite promising.

Interestingly, a realistic estimate of the BH–NS merger rate is $\sim 30\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$ (Abadie et al. 2010), which is compatible with $\mathcal{R}_{\rm macronova}$ estimated here, implying that a BH–NS merger origin for GRB 060614 is indeed plausible.

4. DISCUSSION

Since Li & Paczyński (1998) first proposed that there may be a near-infrared/optical transient following the merger of a compact binary, significant progress has been made in numerical simulations (e.g., Barnes & Kasen 2013; Kasen et al. 2013; Tanaka & Hotokezaka 2013; Tanaka et al. 2014; Kyutoku et al. 2015 and the references therein). Conversely, observational macronova signatures have only been detected for SGRB 130603B (Berger et al. 2013; Tanvir et al. 2013) and the long–short burst GRB 060614 (Yang et al. 2015).

Due to the lack of (detailed) light curves and spectra, the knowledge we can learn is rather limited and the predictions made in the numerical simulations cannot be fully tested. For example, Hotokezaka et al. (2013) showed that for the single macronova data point of SGRB 130603B the NS–NS and BH–NS merger scenarios cannot be distinguished. In the present work, with the assumption that the afterglow data in the time interval of 1.7–3.0 days after GRB 060614 are generated by external FS, we have shown that at late times there are significant excess components in multi-wavelength photometric observations (see Figure 1). There is evidence showing that the associated macronova likely peaked at $t \lesssim 4$ days after the γ-ray transient, which is consistent with current numerical simulations of macronova emission but much earlier than the peak times of GRB-associated SNe.

In the approximation of a thermal spectrum, the temperature of the excess component is inferred to be $\sim$2700 K at $t \sim 13.6$ day. Due to the limited data, no strong evidence for evolution of the temperature can be established. Such a temperature is significantly lower than that of an SN at the same timescale, typically $\sim(0.5\text{–}1) \times 10^4$ K (see, e.g., Della Valle et al. 2006 and Cano et al. 2011), but it is similar to that expected at the photosphere for the recombination of Lanthanides (i.e., $T \sim 2500$ K, see, e.g., Barnes & Kasen 2013). This lends additional support to the neutron-rich nature of macronova ejecta.

We conservatively estimated the macronova rate $\mathcal{R}_{\rm macronova} \sim 16.3^{+16.3}_{-8.2}\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$, and implied that the detection prospect of the gravitational wave radiation from compact-object mergers by the upcoming Advanced LIGO/VIRGO/KAGRA detectors is quite promising, where the expected rate is $\mathcal{R}_{\rm GW} \sim 0.5^{+0.5}_{-0.25}(D/200\ {\rm Mpc})^3\ {\rm yr}^{-1}$.

In the foreseeable future, it is anticipated that increasingly more macronova light curves will be recorded. There could be at least two types of macronova light curves. One group is from NS–NS mergers and the other is from BH–NS mergers. On the one hand, BH–NS mergers are expected to give rise to "bluer," longer, and brighter macronova emission than the NS–NS mergers (e.g., Hotokezaka et al. 2013). On the other hand, the BH–NS merger rate is generally expected to be at most $\sim$1/10 times that of the NS–NS merger rate (Abadie et al. 2010). Hence, if the macronova associated with GRB 060614 indeed arose from a BH–NS merger, its light curve will be different from the majority of the sample that is expected to be from NS–NS mergers.

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