A macronova associated with GRB 070809

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GRB 070809 is a typical short gamma-ray burst (sGRB) detected by the Neil Gehrels Swift Observatory and at the location of the burst no underlying galaxy down to $\sim 28$th AB magnitude in F606W-band has been detected. The X-ray emission was detected quickly after the trigger of the burst and the late time spectrum is very hard. The optical component, substantially brighter than the X-ray extrapolation, is also roughly consistent with a thermal-like emission, and is inconsistent with any afterglow spectrum. Such a peculiar optical to X-ray afterglow spectrum has not been identified previously for any typical sGRBs. The optical component can be naturally interpreted as a blue macronova (also known as kilonova) powered by the lanthanide-poor/free material launched during the neutron star merger. Our finding demonstrates the possibility of revealing the neutron star merger origin with the early afterglow data of some sGRBs that take place well beyond the sensitive radius of the advanced gravitational wave detectors and hence the opportunity of organizing dedicated follow-up observations for events of interest.

The mergers of close compact object binaries are strong gravitational wave (GW) sources and hence prime targets for the advanced LIGO/Virgo detectors.\textsuperscript{2} Short gamma-ray bursts (sGRBs), a kind of brief intense gamma-ray flashes from the space, are widely believed to be generated by the mergers of compact objects involving at least one neutron star.\textsuperscript{2} The outflows of typical/bright sGRBs are ultra-relativistic and narrowly-collimated and hence the GW/GRB association is expected to be rare. The most popular/promising electromagnetic counterparts of the neutron star mergers are suggested to be the Li-Paczynski macronova/kilonova: a near-infrared/optical transient powered by the radioactive decay of heavy material synthesized in the mildly relativistic neutron-rich outflow.\textsuperscript{4} On 2018 August 17, GW170817, the first binary neutron star merger driven gravitational wave event taking place at the redshift of $z = 0.0094$, was successfully detected.\textsuperscript{2} Surprisingly, the gamma-ray monitor onboard the Fermi $\gamma$-ray space telescope also detected an under-luminous/off-axis sGRB at $t \sim 1.7$ sec after the GW signal in the same spatial region.\textsuperscript{2} The world-wide joint ultra-violet/optical/infrared follow-up observations unambiguously identified a bright macronova AT2017gfo (e.g.,\textsuperscript{10,14}). Besides verifying the long-standing speculations on the compact object merger origin of some sGRBs and on the important role of such mergers in generating $r$–process material, the remarkable GW170817/GRB 170817A/AT2017gfo association has also set tight constraints on the superluminal/subluminal motion of gravitational
waves and on the possible violation of weak equivalence principle, rejected the so-called dark matter emulators and a class of cosmic acceleration models, and excluded the binary strange star merger model for sGRBs.

For the GRB/macronova-associated GW signal, the advanced LIGO/Virgo network in the full-sensitivity runs will have a final sensitive distance of $D \sim 400$ Mpc for binary neutron star mergers or $\sim 690$ Mpc for “typical” ($1.4M_\odot - 10M_\odot$) neutron star-black hole mergers. The merger origin of more distant GRBs can not easily be directly established. Fortunately, in the “absence” of a reliable GW detection, the Li-Paczynski macronova serves as a clear signature of neutron star merger. Indeed, before 2017, the identification of macronova signals in sGRB 130603B at $z = 0.356$, GRB 060614 at $z = 0.125$ and sGRB 050709 at $z = 0.16$ has been taken as the most convincing evidence for the compact object merger origin. So far at most a very few typical/bright sGRBs could have been within the sensitive distance of advanced LIGO/Virgo, so the identification of the macronova emission of the main population of typical sGRBs is still essential even in the GW astronomy era. One potential challenge is that, except AT2017gfo, all other macronova signals emerged at $t > 1$ day after the triggers of GRBs when the optical emission was very dim and often hidden by the host galaxy background. Therefore, the optical observations usually require the largest size ground-based instruments or the Hubble Space Telescope (HST). If the macronova candidate can be identified significantly earlier when the source was relatively brighter, it would be very helpful in motivating world-wide follow-up observations. Such efforts are also very important for answering the question: how general is the sGRB/macronova association? Based on the searches of the irregular spectrum in the late optical afterglow emission of sGRBs and also the so-called long-short GRBs, Jin et al. claimed that the sGRB-macronova connection is common. The detection of a bright macronova in GRB 170817A, the first (under-luminous) SGRB with a detected GW signal, supports such a conclusion. Additional support comes from the recent identification of a blue macronova at $t > 1$ day after the trigger of GRB 150101B that is rather similar to the $R$-band signal displaying in GRB 050709, the first SGRB with an identified optical counterpart. Nevertheless, the current sample is rather limited and more GRB/macronova events are highly-needed to confirm/establish the generality of such a kind of association. Motivated by these considerations, we have analyzed some publicly-available sGRB afterglow data and report here the identification of a blue macronova emerging at $t \sim 0.47$ day after the trigger of GRB 070809, a typical SGRB with an early X-ray afterglow that is expected to be an on-axis event.

SGRB 070809 was detected by the Burst Alert Telescope (BAT) onboard Swift satellite at 19:22:17 (UT) on August 9, 2007. The BAT light curve is composed by a single short peak with a duration of $T_{90}(15 - 350$ keV) = 1.3 ± 0.1 s and the time-averaged spectrum is best fitted by a single power-law with a photon index $\beta_\gamma = 1.69 \pm 0.22$. Swift X-ray Telescope (XRT) began to observe the field at 71 seconds after the BAT trigger and detected the X-ray afterglow. The time-averaged X-ray spectrum is fitted by an absorbed power-law model with a column density that is well consistent with the Galactic value, suggesting an ignorable absorption/extinction at the burst site. Swift-UVOT began observing the field at 74 seconds after the BAT trigger but did not find any afterglow. The ground-based ROTSE-IIIc telescope started the observations even more
Table 1. Observations of GRB070809.

| Time (days) | Exposure (seconds) | Instrument | Filter | Magnitude$^{a}$ (AB) |
|------------|-------------------|------------|--------|----------------------|
| 0.44348    | 900               | Gemini-N+NIRI | K      | (> 22.4)             |
| 0.46746    | 1320              | Keck I+LRIS | g      | 25.48 ± 0.20         |
| 0.46767    | 1200              | Keck I+LRIS | R      | 24.54 ± 0.20         |
| 1.47001    | 820               | Keck I+LRIS | g      | (> 25.9)             |
| 1.46867    | 580               | Keck I+LRIS | R      | (> 25.3)             |
| 730.94     | 5150              | HST+ACS    | F606W  | (> 28.0)             |
| 1002.80    | 5597              | HST+WFC3   | F160W  | (> 26.2)             |

Notes. a. These values have not been corrected for the Galactic extinction of $E(B-V) = 0.08$ mag.

promptly (i.e., 30.9 seconds after the trigger) but failed to detect the afterglow either.

At about 0.47 day after the trigger, the Keck telescope observed the field and detected the optical afterglow, which faded away since then. The Gemini telescope took 30×30 seconds images in $K$ band (PI: Paul Price, Gemini proposal ID:GN-2007B-Q-27) started 40 minutes earlier and no infrared afterglow emission was detected. HST observed the burst region in F606W band on 2009-08-09 and F160W band on 2010-05-08 (PI: Andrew Fruchter, HST proposal ID: 11669), respectively. We have downloaded and analyzed the public archive data of Keck, Gemini, HST and XRT. The details of the data analysis are described in the Methods. Generally speaking, our results (see Fig.1 and Tab.1) are nicely in agreement with those reported in the GCN Circulars and Report.

With the HST data, we rule out the presence of a host galaxy coincident with the transient location down to 28.0 mag (AB) in F606W band. Like some sGRBs without strictly coincident host galaxy, GRB 070809 has been found to be close in physical projection to relatively low-redshift galaxies. Two possible host galaxy candidates were discussed before. One is an edge-on spiral galaxy centered at an offset of 5.5′′ to the northwest of GRB 070809 that has a redshift of $z = 0.2187$. The other is an early type galaxy at an offset of 6′′ that has a redshift of $z = 0.473$. The latter has a lower possibility of chance coincidence than the former but the difference is just by a factor of $\sim 4$, indicating that the redshift of GRB 070809 is not secure. In this work, we “conservatively” adopt $z = 0.2187$ since a redshift of 0.473 will not change our results qualitatively but would rank our case the most distant/luminous macronova/kilonova identified so far. With the adopted redshift, GRB 070809 would have an isotropic-equivalent gamma-ray radiation energy $E_{\gamma} > 10^{49}$ erg (we set a lower limit in view of the relatively narrow energy range of Swift BAT), ranking as a “typical”/luminous short event.

The multi-band afterglow lightcurve and spectral energy distribution (SED) of GRB 070809 are presented in Fig.1 and Fig.2 respectively. In comparison to the X-ray emission of GW170817/GRB170817A emerging at $t > 10$ days, GRB 070809 had an early X-ray afterglow starting at $t \leq 71$ s. Such a difference is most-likely due to the off-axis nature of GW170817/GRB 170817A (for a detailed discussion about the outflow structure of this event please see Mooley et al.). Intriguingly, the lightcurves of the optical emission following GW170817/GRB170817A (i.e., AT2017gfo) and GRB 070809 are similar (see Fig.1). The optical to X-ray SED of GRB 070809 measured at $t \sim 0.47$ day, as shown in Fig.2, is distinguished by a rather soft optical component and a very
hard X-ray component. The two components, however, cannot be extrapolated to obtain a typical synchrotron spectrum, being the optical component significantly brighter than any X-ray extrapolation. To our best knowledge, such a SED has not been identified in any other typical sGRBs.

Figure 1: The optical and X-ray “afterglow” lightcurves of GRB 070809 versus that of GW170817/GRB170817A (shifted to a redshift of $z = 0.2187$). As an off-axis event, the optical emission of GW170817 consists of almost solely the macronova (i.e., AT2017gfo) and the X-ray emission emerged only at $t > 10$ days. GRB 070809, instead, has a long-lasting X-ray afterglow that started at $t < 71$ sec after the trigger of the burst, which is an on-axis event. Interestingly, the optical emission of GRB 070809 are similar to, though a bit dimmer than, that of AT2017gfo. For GRB 070809, the UVOT V-band upper limits are adopted from [23] and the early R-band upper limits set by ROTSE-IIIc are taken from [24], the Keck and the XRT data are analyzed in this work. As for GW170817, the optical emission are from [22] and have been corrected to the same intrinsic bands as GRB 070809 by interpolation, while the X-ray data (fluxes at 1.732 keV) are adopted from [23].

The very unusual optical to X-ray spectrum in turn sheds valuable light on the underlying physics. In the standard external shock afterglow model, the optical spectrum can not be softer than the X-ray [26]. One can artificially assume a very high extinction in the “host” galaxy to yield an optical spectrum as hard as that of the X-rays, the corresponding X-ray flux however would be significantly in excess of the observed. Hence it is rather robust to conclude that the optical and X-ray emission have different physical origins. There are two possibilities: (i) the optical emission
Figure 2: The optical to X-ray SED of the afterglow of GRB 070809. The observed (uncorrected for extinction) optical data are plotted, while the blackbody fit takes into account the Galactic extinction $E(B-V) = 0.08$ mag. The X-ray spectrum $\nu^{-0.22\pm0.20}$ is based on the measurements in the late $t^{-1}$ decline phase (i.e., $t > 5000$ s after the trigger of the burst). The optical SEDs of AT2017gfo at two epoches, shifted to the redshift of 0.2187, are also presented for comparison. The optical afterglow of GRB 070809 measured at $t \sim 0.47$ day after the trigger is characterized by a very soft spectrum that can be fitted by a thermal emission with a temperature of $\sim 6000$ K (in the comoving frame), while the X-ray spectrum is rather hard. The significant divergencies between the spectral indexes as well as the fluxes point towards the presence of two kinds of physical emission origins.

was the forward shock emission while the X-ray afterglow was powered by the prolonged activity of the central engine; (ii) the optical afterglow was the blue macronova emission while X-ray afterglow was attributed to either the prolonged activity of the central engine or the forward shock emission. Below we examine these two kinds of possibilities case by case. Since our main concern is the physical origin of the optical emission, here we only present a brief discussion on the X-ray emission. If the X-ray afterglow was given rise by the forward shock, the flat segment calls for either the energy injection from the central engine or a structured outflow, like the modeling of the X-ray flat segment of sGRB 051221A, since the standard fireball afterglow model predicts a much quicker decline (see [B] and the references therein). An additional request is a rather hard shock-accelerated electron spectrum to match the X-ray data. If instead the X-ray afterglow was attributed
The temperature evolution of the macronova signals displaying in GRB 060614 and GRB 070809 (this work) and that of AT2017gfo. The optical component following GRB 070809 has a temperature lower than that of AT2017gfo, indicating the diversity of the macronova emission at early times. The temperatures of the macronova emission of GRB 060614 and AT2017gfo, measured at very late times, are likely the same (~2500 K), as expected at the photosphere for the recombination of Lanthanides.

To the prompt energy dissipation of the continual outflow launched via the prolonged activity of the central engine, the hard spectrum of X-ray emission may be accounted for by the fast-cooling electrons suffering from dominant inverse Compton cooling in the Klein–Nishina regime. The magnetic field in the emitting region, however, should be very low otherwise the Klein–Nishina effect is too weak to modify the energy distribution of electrons and then the radiation spectrum. While for a sGRB that is expected to be powered by the merger of a neutron star binary, a long-lasting (i.e., $10^4 - 10^5$ s) relativistic outflow could be launched by the magnetic process, rather than the neutrino process, given the expected very-low rate ($\ll 10^{-2} M_\odot$ s$^{-1}$) of the fall-back accretion onto the central remnant. So, in the central engine activity model for the X-ray emission, a hard spectrum of electrons accelerated by the magnetic energy dissipation is still needed otherwise the magnetic energy dissipation would have been extremely-efficient in the outflow acceleration phase.

Now let us focus on the more intriguing optical emission. As for the forward shock emission scenario, the main challenge is the unusually soft optical spectrum. The introduction of a high
extinction of the “host” galaxy, for example $A_V \sim 1$ mag for a Small Magellanic Cloud extinction lightcurve at $z = 0.2187$, the “intrinsic” spectrum could become as hard as $\sim \nu^{-1}$ (but harder intrinsic spectra would violate the K-band upper limits), which is still much softer than the observed X-ray spectrum. Moreover, a high extinction is not supported by the low $N_H$ inferred in the X-ray spectrum modeling. Further challenge is the absence of a host galaxy down to 28th mag, as revealed by HST. At a redshift of $z = 0.2187$, such a stringent constraint can only be met by a faint dwarf galaxy like those belonging to the Local Group or the burst took place outside of the host galaxy, no strong extinction is expected in either cases. Therefore, the forward shock afterglow interpretation requires an extremely high power-law index of the accelerated electrons, which in turn would yield a decline too quick to be consistent with the current data. We conclude that the first scenario is strongly disfavored.

The second scenario seems to be much more natural. If interpreted as a blue macronova component at $z = 0.2187$ without suffering from significant extinction, the intrinsic temperature is $\sim 5830^{+1800}_{-700}$ K, which is lower than that of AT2017gfo at a similar time (see Fig.5). The expansion velocity can be estimated to be $V \sim 0.3c (L/10^{44} \text{ erg s}^{-1})^{1/2} (T/6000 \text{ K})^{-2} (t/0.5 \text{ day})^{-1}$, where $c$ is the speed of the light and $L$ is the luminosity of the macronova emission. The mass of the lanthanide-poor/free wind is estimated to be $M_{ej} \sim 0.015 M_\odot (V/0.3c)(t/0.5 \text{ day})^2 (\kappa/0.2 \text{ cm}^2 \text{ g}^{-1})^{-1}$ and comparable to that inferred from the modeling of AT2017gfo, where $\kappa$ is the opacity parameter of the sub-relativistic lanthanide-poor/free outflow. Though the initial dynamical ejecta of compact object mergers are expected to be lanthanide-rich, due to the absorption of neutrinos from the nascent pre-collapse massive neutron star or the accretion disk at high latitudes, some material will become lanthanide-poor/free. A relatively long-lived accretion disk can also launch lanthanide-poor/free material. Our finding is support of these theoretical predictions. The red macronova component of GRB 070809, which should have lasted 1-2 weeks, however was too soft/dim ($\sim 26$th AB magnitude in H-band at $t \sim 10$ day after the burst if we simply shift AT2017gfo to $z = 0.2187$) to be caught even by ground-based very large size telescopes at such a redshift.

Note that the early emission of AT2017gfo was also dominated by a blue macronova, implying that the formation of a relatively long-lived accretion disk and/or a somewhat delayed collapse of the nascent remnants formed in the neutron star mergers may be typical. If confirmed, this would provide the valuable chance to reveal the neutron star merger origin of some GRBs that are well beyond the sensitive distance of the advanced gravitational wave detectors like LIGO and Virgo. This could be in particular the case for some distant sGRBs with very faint forward shock optical afterglow emission. Quick follow-up photometric observations of such sGRBs could yield significant evidence for the emergence of a macronova at earlier times, as reported in this work for GRB 070809. For similar intriguing events discovered in the future, world-wide follow-up observations with large size ground-based telescopes can be effectively organized and the late time HST observations should be carried out to catch the red macronova component. Most of the merger-driven GRBs with GW data from advanced LIGO/Virgo will appear as under-luminous events since the energetic outflow core will be viewed off-axis, while the typical sGRBs at relatively high redshifts are usually on-axis events. A large GRB/macronova sample consisting of both
types of events would be essential in examining the angular dependence of the ejecta (including the nucleosynthesis products) and the generality of such a kind of association thoroughly.

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Methods

The Optical Data Analysis. For the Keck telescope observations, we have downloaded the public archive data together with the necessary calibration frames including bias, flat and standard stars. Standard recipes (bias subtraction, flat-field normalization, etc.) were applied for data reduction. The science frames in the same band and same night were simply added. The optical counterpart is very close to a bright star at (13:35:03.597, -22:08:42.30) and the background is thus contaminated. The source and the standard star flux were measured using small apertures to maximize the S/N ratio and finally corrected to infinite apertures. The background, estimated in the “blank” regions which are at angular separation from the bright star similar to that of GRB 070809, has been subtracted from the signal. A standard star PG0231+051, SDSS $g'$=15.729 ± 0.004 mag (AB) and Johnson R = 16.240 ± 0.008 mag (Vega), was observed 5 times in both $g$ and $R$ bands on Aug. 11 2007. These frames are used to determine zero point of that night. In the application to the science images on Aug. 11 2007, the atmosphere extinctions of 0.15 mag/airmass in $g$ band and 0.11 mag/airmass in $R$ band have been taken into account (Atmosphere extinctions were taken from experimental extinction value of Mauna Kea, Hawaii, which are available at https://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/extinction). The uncertain introduced in this process is estimated to be 0.05 mag, which has been added to the final error. Due to the absence of standard star observation on Aug. 10 2007, we calibrate the science images with some bright unsaturated reference stars, well measured on both Aug. 10 and Aug. 11 2007. All these procedures are performed by means of IRAF tools (http://iraf.noao.edu).

For Gemini, the data reduction are essentially similar to Keck except one more step to subtract the dark current is applied. There was no standard observation in that night, and a statistical zero point 23.43 for $K$ is adopted in our analysis.

For HST data, we downloaded the full reduced production data, and measure the RMS of the GRB position. The $3\sigma$ upper limits are then set accordingly.

The XRT Data Analysis. The X-ray telescope (XRT) onboard Neil Gehrels Swift Observatory observed the field of GRB 070809 for three times (ObsIDs: 00287344000, 00287344001 and 00287344002). The XRT photon counting (PC) mode data are analyzed by the FTOOLS software version 6.22.1 and the initial event cleaning with the xrtpipeline using standard quality cuts has been carried out. Then the source spectra and light curve within a circular region with a radius of 20 pixels are extracted with xselect while the background ones are also extracted via a larger circle (i.e. 50 pixels) in a blank area. We produce the ancillary response file with xrtmkarf to facilitate the spectral analysis, in which the response files were taken from the CALDB database. The grouped spectra are demanded to have at least 1 count per bin using the cstat approach and the parameter of absorption is set as the Galactic value (i.e. $N_H = 8.59 \times 10^{20} \text{ cm}^{-2}$) during the analysis since there is no evidence for significant absorption at the burst site. A hardening of the XRT spectra is suggested by the hardness ratio data (see http://www.swift.ac.uk/xrt_curves/002873444/). Therefore we divide the XRT data in two intervals, with an early one (from $\sim 80$ s to 1958 s) and a late one ($t > 5322$ s) that follows a $\sim t^{-1}$ decline. The early and the late XRT spectra are well fit-
ted by $f \propto \nu^{-0.60 \pm 0.28}$ and $\propto \nu^{-0.22 \pm 0.20}$, respectively, which do show some evidence for a spectral hardening. Our results are well consistent with the automatic analysis results provided by the Swift XRT team (http://www.swift.ac.uk/xrt_spectra/00287344/; see [1] for the analysis methods), which are $\nu^{-0.57 \pm 0.14}$ and $\nu^{-0.21 \pm 0.16}$, respectively. Meanwhile, exposure correction of the light curve has been performed by `xrtlccorr` and it is binned with roughly 20 counts per bin. The exception is the last time bin (i.e., the third XRT observation) which contains in total eight net photons.

References

1. Evans, P. A., Beardmore, A. P., Page, K. L., et al. Methods and results of an automatic analysis of a complete sample of Swift-XRT observations of GRBs. *Mon. Not. R. Astron. Soc.*, 397, 1177 (2009)