Search Capability for Kilonova Associated with a Short Gamma-Ray Burst with SVOM (Postprint)

Authors: J. Wang, L. P. Xin, Y. L. Qiu, L. Lan, W. J. Xie, Z. P. Jin and J. Y. Wei

Date: 2024-12-06T00:00:00+00:00

Abstract

In spite of the importance of studying the cosmic generation of heavy elements through the r-process, the detection of a kilonova resulting from the merger of a neutron star binary is still a challenging task. In this paper, we show that the Visible Telescope (VT) onboard the ongoing SVOM space mission is powerful for identifying kilonova candidates associated with short gamma-ray bursts up to a distance of 600 Mpc. A significant color variation, turning blue and then turning red, is revealed by calculating the light curves in both red and blue channels of VT by a linear combination of an afterglow and an associated kilonova. The maximum color variation is as high as 0.5–1 mag, which is far larger than the small photometry error of 0.2 mag of VT for a point source with a brightness of 23 mag. Up to a distance of 600 Mpc, 1–2 kilonova candidates per year are predicted to be identified by VT.

Full Text

Preamble

Research in Astronomy and Astrophysics, 24:115006 (5pp), 2024 November

https://doi.org/10.1088/1674-4527/ad7fb5

Capability of Searching for Kilonova Associated with a Short Gamma-Ray Burst by SVOM

J. Wang[1],[2], L. P. Xin[1], Y. L. Qiu[1], L. Lan[1], W. J. Xie[1], Z. P. Jin[3], and J. Y. Wei[1]
[1] Key Laboratory of Space Astronomy and Technology, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China;

wj@nao.cas.cn
[2] Guangxi Key Laboratory for Relativistic Astrophysics, School of Physical Science and Technology, Nanning 530004, China
[3] Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023, China

Received 2024 July 20; revised 2024 August 28; accepted 2024 September 23; published 2024 October 30

Abstract

Despite the importance of studying the cosmic generation of heavy elements through the r-process, detecting a kilonova resulting from the merger of a neutron star binary remains a challenging task. In this paper, we demonstrate that the Visible Telescope (VT) onboard the ongoing SVOM space mission is powerful for identifying kilonova candidates associated with short gamma-ray bursts up to a distance of 600 Mpc. By calculating the light curves in both red and blue channels of VT through a linear combination of an afterglow and an associated kilonova, we reveal a significant color variation that turns blue and then red. The maximum color variation is as high as 0.5–1 mag, which is far larger than the small photometry error of 0.2 mag of VT for a point source with a brightness of 23 mag. Up to a distance of 600 Mpc, 1–2 kilonova candidates per year are predicted to be identified by VT.

Key words: instrumentation: photometers – telescopes – stars: neutron – (stars:) gamma-ray burst: general

1. Introduction

The merger of a neutron star binary, which itself manifests as gravitational wave (GW) radiation (e.g., Abbott et al. 2020), is predicted to produce a short-duration gamma-ray burst (SGRB, T90 $<$ 2 s, e.g., Kouveliotou et al. 1993) and an associated kilonova (e.g., Eichler et al. 1989; Li & Paczyński 1998; Freiburghaus et al. 1999; Rosswog et al. 1999; Perego et al. 2014; Just et al. 2015). The kilonova is powered by the radioactive decay of isotopes of heavy elements assembled via rapid neutron capture (r-process) nucleosynthesis in the matter expelled by the merger (e.g., Burbidge et al. 1957; Metzger et al. 2010; Korobkin et al. 2012; Barnes & Kasen 2013; Kasen et al. 2013, 2017; Barnes et al. 2016; Metzger 2019; Chen et al. 2024).

Although SGRBs have been frequently detected by past and ongoing gamma-ray burst (GRB) missions (see review in Berger 2014), detecting the associated kilonova remains a difficult task at the current stage (e.g., Troja 2023). In fact, only two have been confirmed by spectroscopy in the literature. The first case, AT 2017gfo associated with a weak SGRB GRB 170817A, was found by the Swope Supernova Survey during a campaign searching for the electromagnetic counterpart of GW170817 discovered by the LIGO-Virgo experiments (e.g., Abbott et al. 2017a, 2017b; Andreoni et al. 2017; Arcavi et al. 2017; Covino et al. 2017; Cowperthwaite et al. 2017; Drout et al. 2017; Evans et al. 2017; Goldstein et al. 2017; Kilpatrick et al. 2017; Smartt et al. 2017; Tanaka et al. 2017). The kilonova identification was confirmed by comparing its spectroscopic sequence obtained by large telescopes with spectral models (e.g., Pian et al. 2017; Shappee et al. 2017).

The second case is GRB 230307A, a long-duration GRB at $z = 0.065$, in which Levan et al. (2024) recently identified an emission line of tellurium (atomic mass $A = 130$) from mid-infrared spectroscopy and imaging taken by the James Webb Space Telescope dozens of days after the trigger. In addition to these two spectroscopically confirmed cases, a batch of kilonova candidates has been identified by modeling multi-wavelength light curves due to an excess of near-infrared (NIR) emission a couple of days after the GRB trigger (e.g., Berger et al. 2013; Fan et al. 2013; Tanvir et al. 2013; Jin et al. 2015, 2016, 2018, 2020, 2021; Yang et al. 2015; Troja et al. 2018, 2019; Lamb et al. 2019; Rastinejad et al. 2022; Zhu et al. 2023; Troja et al. 2022; Yang et al. 2024).

In this paper, we demonstrate that the Visible Telescope (VT) onboard the Space Variable Objects Monitor (SVOM) satellite enables us to easily identify kilonova candidates up to a distance of 600 Mpc according to their strong NIR excess. The main reason is that the red channel of VT has quite deep sensitivity up to a wavelength of 1 m due to the lack of strong NIR atmospheric emission in space. The paper is organized as follows. Section 2 briefly describes the payloads of the SVOM mission, especially the capability of VT. The calculations of the optical light curves observed by VT are presented in Section 3. Section 4 gives the results and implications. Conclusions are stated in Section 5.

2. Instruments Onboard SVOM

SVOM, launched on 2024 June 22, is a Chinese-French space mission dedicated to the detection and study of GRBs. We refer readers to Atteia et al. (2022) and the white paper by Wei et al. (2016) for details.

There are four onboard instruments. The wide-field soft γ-ray imager ECLAIRs and Gamma-Ray Monitor (GRM) are designed to observe GRB prompt emission in 4–150 keV and 15–5000 keV energy bands, respectively. With a field-of-view (FoV) of 2 sr and a sensitivity of 7.2×10^{-10} erg s^{-1} cm^{-1} (5σ in an exposure of 1000 s), ECLAIRs can trigger 60–70 GRBs per year (Godet et al. 2014; Cordier et al. 2015). In addition, with a detection area of 200 cm^2 for each Gamma-Ray Detector (GRD) module, 90 GRBs are expected to be detected per year by GRM.

The narrow-field Microchannel X-ray Telescope (MXT, Gotz et al. 2014) and VT are responsible for follow-up observations of afterglows in X-ray and optical wavelengths, respectively. VT is a Ritchey-Chrétien telescope with a 43 cm diameter and an f-ratio of 9. It has an FoV of about 26 × 26 arcmin^2, covering ECLAIR's error box in most cases. The limiting magnitude is down to m_V =

22.5 mag for a 300 s exposure. With a dichroic beam splitter, VT works in two channels, one in blue and the other in red, simultaneously. The blue channel has a wavelength range from 0.4 to 0.65 m, and the red one from 0.65 to 1.0 m. Each channel is equipped with a 2k × 4k E2V frame transfer CCD, with a back-illuminated thick CCD used for the red channel to enhance the quantum efficiency (QE).

The left panel in Figure 1 shows the total throughput curves of the two channels, along with the corresponding transmittance of the filters and the QE of the two CCDs. A more detailed description of the calibration and determination of the throughput curves can be found in Y. L. Qiu et al. (2024, in preparation). With the throughput curves, the limiting magnitudes in the two channels are calculated by the dedicated Exposure Calculator of VT^4 according to the simplified "CCD" equation (Mortara & Fowler 1981; Gullixson 1992; Merline & Howell 1995; see NOAO/KPNO CCD instrument manuals), where N , N_b, and N_d are the photon rate from the source, the photon rate per pixel from sky background, and dark current per pixel, respectively. t is the exposure time and R_N the readout noise of each pixel. n_{pix} and   are the number of pixels occupied by a single star and the system total throughput, respectively. The limiting magnitudes in both channels are plotted in the right panel of Figure 1 as a function of exposure time for a power-law f_ $^{-1.3}$ (typical of a GRB, see below) at two significance levels of 3σ and 5σ.

Basically, for an exposure of 300 s, the limiting magnitudes are 23.4 and 23.1 for the blue and red channels, respectively, at a significance level of 3σ. The corresponding values degrade to 22.9 and 22.6 at a significance level of 5σ.

3. Calculation of Theoretical Light Curves

To examine the capability of identifying kilonova candidates, we calculate a set of light curves recorded in both VT channels by a linear combination of an SGRB's afterglow and an associated kilonova.

3.1 Afterglow from SGRB

We calculate the evolution of the luminosity of an afterglow by adopting the simple and widely used power-law: F_ t^α ^β. The values of α and β are fixed to be 1.3 and 1.2, respectively, for a late afterglow (i.e., at about 1 day after a trigger and ignoring the possible jet break effect) throughout the paper. The coefficient of the power-law is determined from a sample of normalized light curves of SGRBs (e.g., Nicuesa Guelbenzu et al. 2012). Specifically, the brightness in the R_c-band at 1 day is adopted to be from 29 to 25 mag in the z = 1 reference frame.

3.2 Emission from Kilonova

We adopt the spectral model grid developed by Kasen et al. (2017)[5] to calculate the specific luminosity L_ ^{kn} of a given kilonova at a given time. In the model, the mergers of two neutron stars are simulated in general relativity, in which material is ejected via two distinct mechanisms. One with a high velocity of 0.2–0.3c results from the dynamical expulsion of matter from the surface of the approaching stars due to tidal forces, along with the squeezing of matter at the interface. The other low-velocity (0.05–0.1c) ejection is caused by winds from the accretion disk formed around the central remnant after the merger. The ejecta is assumed to be spherically symmetric with a density profile of $^{-1}$ and $^{-10}$ in the inner and outer layers, respectively. The emission resulting from the decay of radioactive r-process isotopes is calculated by solving the time-dependent radiative transfer equation under local thermodynamic equilibrium, in which millions of bound-bound transitions are considered to obtain the opacities, including all lanthanides. The model grid provides spectra from ultraviolet to infrared every 0.1 days after a merger. In addition to the fixed exponents of the inner and outer density profile, the parameters of the model grid are: ejecta mass 0.001 ≤ m/M_ ≤ 0.1, kinetic velocity of the ejecta 0.03 ≤ v_k/c ≤ 0.3, and the mass fraction of lanthanides 10^{-9} ≤ X_{lan} ≤ 10^{-1}.

3.3 Predicted Light Curves Recorded by VT

With the time-resolved spectra of both afterglow and kilonova described above, the light curves recorded in the two VT channels (denoted by B_{VT} and R_{VT} for the blue and red channels, respectively) are calculated according to the definition of the AB magnitude (Fukugita et al. 1996): 2.5 log 48.6, where S_ is the total throughput at frequency as given in Figure 1. f_ is the specific flux density of an object in units of erg s^{-1} cm^{-2} Hz^{-1}, and is calculated from the predicted luminosity L_ as f_ = L_ /4πd^2, where d is the distance.

4. Results

Figure 2 compares the predicted light curves between an afterglow and a kilonova at distances of 40 Mpc (upper panel) and 600 Mpc (lower panel). In each panel, the boundaries of the afterglow are inferred for two extreme cases: a strong afterglow with m_{Rc} = 25 mag and a weak afterglow with m_{Rc} = 29 mag, where m_{Rc} is the brightness in the R_c-band at 1 day in the z = 1 reference frame. The kilonova light curves are obtained from model spectra with m = 0.05 M_ , v_k = 0.3c, and X_{lan} = 10^{-4}.

Three facts can be learned from the figure. First, the two VT channels reproduce the well-known infrared excess of a kilonova at the late epoch of 1 day, which will be addressed in more detail below. Second, in the red channel, the light curve at 1 day after a trigger can be dominated by a kilonova if the associated afterglow is quite weak (or off-axis). Finally, with the limiting magnitude of 22.5 mag, a kilonova candidate can be identified in the VT red channel at a distance as far as 600 Mpc.

Figure 3 shows the predicted temporal evolution of $B_{VT} - R_{VT}$ color obtained by VT for the entire kilonova spectral model grid given in Kasen et al. (2017). The fiducial model is again adopted to be the one with m = 0.05 $M_{}$, $v_k = 0.3c$, and $X_{lan} = 10^{-4}$. In addition to the strong and weak afterglow cases, cases with an intermediate afterglow level with $m_{Rc} = 27$ mag are shown in the middle column. One can see from the figure a significant color variation in almost all cases, in which the light curves become blue at early epochs and transform to red at late epochs. The weaker the associated afterglow, the larger the value of color difference $\Delta(B_{VT} - R_{VT})$ will be. The maximum $\Delta(B_{VT} - R_{VT})$ is as high as 0.5–1 mag. It is noted that $\Delta(B_{VT} - R_{VT})$ is in fact independent of the spectral shape of the associated afterglow as long as its spectral index stays constant. This revealed trend is consistent with the theoretical evolution of a kilonova, where the kilonova spectrum is dominated by the "blue" (light r-process) component at the beginning, and then by the "red" (heavy r-process) component after a couple of days.

We argue that there is agreement between the spectral model and the dependence of the calculated color evolution on kilonova parameters. First, the top row in Figure 3 shows that a larger ejecta mass produces a brighter kilonova that results in a redder spectrum, which is consistent with the scaling law for characteristic luminosity $L \quad m^{0.35}v^{0.65}\ {}^{-0.65}$, i.e., Equation (3) in Kasen et al. (2017), where is the opacity being sensitive to X_{lan}: the larger the X_{lan}, the larger the will be. Second, Equation (2) in Kasen et al. (2017) leads to a duration of kilonova $t \quad m^{1/2}v^{-1/2}\ {}^{1/2}$. This scaling law implies a shorter-lasting kilonova for higher velocity, which can be seen in the middle row of the figure. Finally, the bottom row in the figure shows the dependence on X_{lan}. For cases with large $X_{lan} > 10^{-2}$, the corresponding large opacity causes kilonova emission to appear primarily in the infrared (i.e., the heavy r-process component), which results in a reduced effect on the optical color. On the contrary, a large variation of optical color can be revealed in cases with small $X_{lan} < 10^{-4}$, in which the kilonova emission in the optical bands is dominated by the light r-process component that decays and cools with time.

Based on our calculations, we conclude that VT is powerful for identifying a kilonova associated with an SGRB through the measured color variation of the afterglow. In fact, VT has typical photometry errors of 0.01 and 0.2 mag for point sources with brightnesses of 16 and 23 mag, respectively, which enable us to identify a kilonova candidate at distances up to 600 Mpc by VT. At this distance, in the case with a strong associated afterglow, the $B_{VT} - R_{VT}$ color is predicted to change by 0.4 mag for the fiducial kilonova model with m = 0.05 $M_{}$, $v_k = 0.3c$, and $X_{lan} = 10^{-4}$ (i.e., the red lines in Figure 3). This predicted color change is slightly larger than the measured color error of 0.3 mag.

5. Conclusion and Implications

The light curves in both red and blue channels of VT onboard the SVOM satellite are predicted by a linear combination of an SGRB afterglow and an associated kilonova. The predicted light curves show a significant color variation with a maximum value as high as 0.5–1 mag. With its detection limit and accuracy, VT is therefore powerful for identifying kilonova candidates up to a distance of 600 Mpc.

We estimate the detection rate of kilonovae by VT as follows. Based on the recent BATSE GRB catalog[6], there are 500 SGRBs with T90 < 2 s among 2041 events, which yields an SGRB fraction of 1/4 in the BATSE sample. Since the GRM onboard SVOM has a comparable energy range with BATSE, 20 SGRBs in total are predicted to be detected per year by GRM. Among these 20 SGRBs, 1–2 SGRBs are expected to have a luminosity distance up to 600 Mpc by assuming the SGRBs detected by GRM follow the redshift distribution of SGRBs given in Berger (2014), which leads to a kilonova detection rate of 1–2 yr^{-1} by VT onboard SVOM.

Acknowledgments

The authors would like to thank the anonymous referee for their careful review and helpful comments. This study is supported by the Strategic Pioneer Program on Space Science, Chinese Academy of Sciences, grant XDB0550401. J.W. is supported by the National Natural Science Foundation of China (NSFC, grant No. 12173009), by the Natural Science Foundation of Guangxi (2020GXNSFDA238018) and by the Bagui Young Scholars Program. L.L. is supported by the National Postdoctoral Program for Innovative Talents (grant No. GZB20230765).

References

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017a, ApJL, 850, L40
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017b, ApJL, 851, L16
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2020, LRR, 23, 3
Andreoni, I., Ackley, K., Cooke, J., et al. 2017, PASP, 34, e069
Arcavi, I., Hosseinzadeh, G., Howell, D. A., et al. 2017, Natur, 551, 64
Atteia, J.-L., Cordier, B., & Wei, J. 2022, IJMPD, 31, 2230008
Barnes, J., & Kasen, D. 2013, ApJ, 775, 18
Barnes, J., Kasen, D., Wu, M.-R., et al. 2016, ApJ, 829, 110
Berger, E. 2014, ARA&A, 52, 43
Berger, E., Fong, W., & Chornock, R. 2013, ApJL, 774, L23
Burbidge, E.M., Burbidge, G.R., Fowler, W.A., & Hoyle, F. 1957, RvMP, 29, 547
Chen, M.-H., Li, L.-X., Chen, Q.-H., et al. 2024, MNRAS, 529, 1154
Cordier, B., Wei, J., Atteia, J. L., et al. 2015, arXiv:1512.03323
Covino, S., Wiersema, K., Fan, Y. Z., et al. 2017, NatAs, 1, 791

Cowperthwaite, P. S., Berger, E., Villar, V. A., et al. 2017, ApJL, 848, L17
Drout, M. R., Piro, A. L., Shappee, B. J., et al. 2017, Sci., 358, 1570
Eichler, D., Livio, M., Piran, T., et al. 1989, Natur, 340, 126
Evans, P. A., Cenko, S. B., Kennea, J. A., et al. 2017, Sci., 358, 1565
Fan, Y.-Z., Wu, X.-F., & Wei, D.-M. 2013, PhRvD, 88, 067304
Freiburghaus, C., Rosswog, S., & Thielemann, F.-K. 1999, ApJL, 525, L121
Fukugita, M., Ichikawa, T., Gunn, J. E., et al. 1996, AJ, 111, 1748
Godet, O., Nasser, G., Atteia, J., et al. 2014, Proc. SPIE, 9144, 914424
Goldstein, A., Veres, P., Burns, E., et al. 2017, ApJL, 848, L14
Gotz, D., Adami, C., Basa, S., et al. 2014, in Proc. of Swift: 10 Years of Discovery (SWIFT 10), ed. P. Caraveo, P. D'Avanzo, N. Gehrels et al. (Trieste: SISSA)
Gullixson, C. A. 1992, in ASPC: Astronomical CCD observing and reduction techniques, 23, ed. S. B. Howell (San Francisco, CA: ASP), 139
Jin, Z.P., Covino, S., Liao, N.H., et al. 2020, NatAs, 4, 77
Jin, Z.-P., Hotokezaka, K., Li, X., et al. 2016, NatCo, 7, 12898
Jin, Z.-P., Li, X., Cano, Z., et al. 2015, ApJ, 811, L22
Jin, Z.-P., Li, X., Wang, H., et al. 2018, ApJ, 857, 128
Jin, Z. P., Zhou, H., Covino, S., et al. 2021, arXiv:2109.07694
Just, O., Obergaulinger, M., & Janka, H.-T. 2015, MNRAS, 453, 3386
Kasen, D., Badnell, N. R., & Barnes, J. 2013, ApJ, 774, 25
Kasen, D., Metzger, B., Barnes, J., et al. 2017, Natur, 551, 80
Kilpatrick, C. D., Foley, R. J., Kasen, D., et al. 2017, Sci., 358, 1583
Korobkin, O., Rosswog, S., Arcones, A., et al. 2012, MNRAS, 426, 1940
Kouveliotou, C., Meegan, C. A., Fishman, G. J., et al. 1993, ApJL, 413, L101
Lamb, G. P., Tanvir, N. R., Levan, A. J., et al. 2019, ApJ, 883, 48
Levan, A. J., Gompertz, B. P., Salafia, O. S., et al. 2024, Natur, 626, 737
Li, L.-X., & Paczyński, B. 1998, ApJL, 507, L59
Metzger, B. D. 2019, LRR, 23, 1
Metzger, B. D., Martínez-Pinedo, G., Darbha, S., et al. 2010, MNRAS, 406, 2650
Nicuesa Guelbenzu, A., Klose, S., Greiner, J., et al. 2012, A&A, 548, A101
Merline, W.J., & Howell, S.B. 1995, ExA, 6, 163
Mortara, L., & Fowler, A. 1981, in SPIE Conference Proceedings, 290, 28
Perego, A., Rosswog, S., Cabezón, R. M., et al. 2014, MNRAS, 443, 3134
Pian, E., D'Avanzo, P., Benetti, S., et al. 2017, Natur, 551, 67
Rastinejad, J. C., Gompertz, B. P., Levan, A. J., et al. 2022, Natur, 612, 223
Rosswog, S., Liebendörfer, M., Thielemann, F.-K., et al. 1999, A&A, 341, 499
Shappee, B. J., Simon, J. D., Drout, M. R., et al. 2017, Sci., 358, 1574
Smartt, S. J., Chen, T.-W., Jerkstrand, A., et al. 2017, Natur, 551, 75
Tanaka, M., Utsumi, Y., Mazzali, P. A., et al. 2017, PASJ, 69, 102
Tanvir, N. R., Levan, A. J., Fruchter, A. S., et al. 2013, Natur, 500, 547
Troja, E. 2023, Univ, 9, 245
Troja, E., Fryer, C. L., O'Connor, B., et al. 2022, Natur, 612, 228
Troja, E., Ryan, G., Piro, L., et al. 2018, NatCo, 9, 4089
Troja, E., Castro-Tirado, A. J., Becerra Gonzlez, J., et al. 2019, MNRAS, 489,

2104
Wei, J. Y., Cordier, B., Antier, S., et al. 2016, arXiv:astro-ph/1610.0689
Yang, B., Jin, Z.-P, Li, X., et al. 2015, NatCo, 6, 7323
Yang, Y.-H., Troja, E., O'Connor, B., et al. 2024, Natur, 626, 742
Zhu, Y.-M., Zhou, H., Wang, Y., et al. 2023, MNRAS, 521, 269

Note: Figure translations are in progress. See original paper for figures.