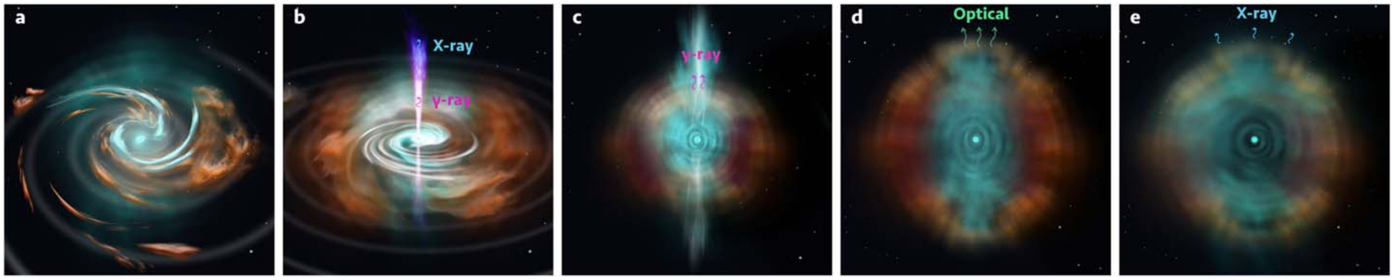

Figure 16. Artist impression of the different energy sources powering the GRB 180618A multiwavelength emission. (a) The material is equatorially ejected by tidal forces during the neutron star binary merger (Cucchiara et al. 2011) and radially ejected by hydrodynamic interactions at the neutron stars contact region (e.g., Metzger 2019). (b) The accretion of the torus onto a rotationally supported supramassive neutron star remnant (i.e., a millisecond magnetar) powers two relativistic jetted outflows (Bucciantini et al. 2012; Metzger et al. 2018) that, via internal dissipation mechanisms, produce the initial ≈0.3 s hard prompt gamma-ray emission. At this stage, the accretion disk releases winds that largely dominate the total mass ejected (Margalit & Metzger 2019). (c) The winds from the rotationally powered magnetar are collimated by the surrounding ejecta, which give rise to the ≈45 s duration soft gamma-ray emission (Bucciantini et al. 2012). (d) As the spin-down luminosity of the magnetar decreases, the jetted winds become stifled behind the ejecta, which is reheated at larger radii. When the opacity of the ejecta decreases sufficiently, bright optical thermal emission is emitted (Yu et al. 2013; Metzger & Piro 2014; Metzger 2019). (e) Hours after the merger, the ejecta is fully ionized by the winds of the long-lived magnetar, and the magnetar spin-down luminosity is detected (Metzger & Piro 2014).

5. Discussion

The early-time multiwavelength observations of short GRB 180618A propose a scenario in which only a long-lived magnetar remnant can account for all the observed emission components (see Figure 16): the extended soft gamma-ray emission following the short GRB (Metzger et al. 2008; Bucciantini et al. 2012), the unusual optical light curve (Yu et al. 2013; Metzger & Piro 2014), and the additional X-ray component (Metzger & Piro 2014; Gao et al. 2015).

Tens of magnetars have been identified in our Galaxy so far (Kaspi & Beloborodov 2017), and some of them are regular X-ray bursters that, less frequently, emit at soft gamma-ray bands (Ridnaia et al. 2021). More recently, giant flares from extragalactic magnetars have also been associated with low-luminosity short-duration GRBs (Svinkin et al. 2021). However, the remnant of a neutron star binary merger is expected to be the more energetic version of a magnetar, a millisecond protomagnetar (Metzger & Piro 2014), which is rotationally powered with typical energies $E_{\rm rot} \approx 10^{51}$–$10^{53}$ erg, and will spin down until its collapse into a black hole (Margalit & Metzger 2019).

After a neutron star binary merger, if a newborn rapidly spinning magnetar has sufficient spin-down luminosity, the winds will pierce through the ejecta and be collimated into bipolar jetted outflows that will dissipate Poynting-flux energy—powering the extended gamma-ray emission of GRB 180618A (Metzger et al. 2008; Bucciantini et al. 2012). As the spin-down luminosity of the magnetar decreases with $L_{\rm sd} \propto t^{-2}$, these winds are trapped behind the ejecta forming a hot nebula of electron–positron pairs that will radiate via synchrotron and inverse Compton emission (Metzger & Piro 2014). A fraction of the X-ray emission is then absorbed by the neutral ejecta walls and reprocessed into optical and infrared photons that are able to escape when the optical depth of the expanding ejecta decreases enough. This allows the magnetar-powered kilonova of GRB 180618A to be a hundred times brighter than a radioactively powered kilonova (Yu et al. 2013; Metzger & Piro 2014). Hours to days after the burst, if the strong magnetar winds can completely ionize the ejecta, nonthermal X-ray emission will leak from the nebula producing an X-ray excess (Metzger & Piro 2014), similar to that observed ≈0.5 days after GRB 180618A.

Our multiwavelength data also gives information about the geometry of the system. Given that we are detecting prompt gamma-ray emission that is bright and spectrally hard, we are likely facing the GRB jet (Yamazaki et al. 2002). If the magnetar is releasing energy and accelerating ejecta along the polar regions of the system, material can easily reach transrelativistic speeds (Metzger et al. 2008; Bucciantini et al. 2012). This extra kinetic energy is consistent with what we observe at optical bands; there is an early and rapid evolution of the thermal luminosity given the relativistically expanding photospheric radius and the fast-fading spin-down luminosity of the magnetar, which we measure as $L_{\rm th} \propto t^{-(2.22\pm0.14)}$. For the optical to be reprocessed within the observed timescales, we require an ejecta mass $M_{\rm ej} \lesssim 10^{-4} M_\odot (\kappa_\pm/10^3)^{-1}$ at the polar regions of the merger, which is reasonable given that a total ejected mass $\approx (0.01$–$0.3) M_\odot$ is expected in all directions (Oechslin & Janka 2006; Murguia-Berthier et al. 2017). This suggests that the merger ejecta distribution is considerably asymmetric, likely due to long-lasting cavities drilled by the early relativistic outflows or the disk winds ejecting more material in equatorial directions (Bucciantini et al. 2012).

Current magnetohydrodynamic simulations cannot form jetted outflows just from the neutron star binary merger itself (Ruiz & Shapiro 2017); successful jets require the formation and delayed collapse within a hundred milliseconds of an intermediate hypermassive neutron star (Murguia-Berthier et al. 2014). However, constraints on the nuclear equation of state suggest that 18%–65% of the neutron stars binary mergers will result in a less massive and rotationally supported supramassive neutron star remnant with longer lifetime (Fryer et al. 2015; Margalit & Metzger 2019). Without the need for the neutron star remnant to collapse into a black hole, a viable short GRB from a merger could be powered by direct accretion onto the magnetar (Bucciantini et al. 2012), or by the enhancement of the spin-down luminosity given the temporary presence of the accretion disk (Metzger et al. 2018). Yet, baryon pollution remains a concern in these environments (Lee & Ramirez-Ruiz 2007; Murguia-Berthier et al. 2014).

The multiwavelength data set of GRB 180618A confirms GW170817/GRB 170817A findings (Abbott et al. 2017b)—i.e., neutron star binaries as progenitors of short GRBs. While the remnant of gravitational wave event GW170817 is likely a hypermassive neutron star that collapsed into a black hole within the first few hundreds of milliseconds after the merger

(Abbott et al. 2017b; Metzger 2019), observations of short GRB 180618A suggest a different outcome. We observe that a vast energy reservoir is injected into the system on timescales much larger than the duration of the accretion disk outflows—powering several emission components across the spectrum that can only be explained by a long-lived magnetar remnant. Furthermore, it suggests that supramassive neutron stars with delayed collapse into a black hole are remnants of neutron star binary mergers (Fryer et al. 2015; Margalit & Metzger 2019), and can power short hard GRBs and extended soft gamma-ray emission through accretion and spin-down luminosity (Metzger et al. 2008; Bucciantini et al. 2012). These findings preserve a good agreement between the percentage of short GRBs that have extended emission (13%–50%; Norris et al. 2010; Lien et al. 2016), and the expected number of remnants from neutron star binary mergers that can power such emission (18%–65%; Margalit & Metzger 2019).

Future early-time studies of short GRBs with extended gamma-ray emission and joint GW/GRB detections will be able to statistically constrain how long and how many of these cosmological magnetars survive the merger, characterize the asymmetries in the distribution of the ejected mass, and probe jet acceleration in millisecond magnetars.

6. Conclusions

We report the multiwavelength observations of short GRB 180618A; a GRB with unique gamma-ray, X-ray, and optical properties result of a compact object binary merger at the outskirts of a galaxy at redshift $z = 0.554 \pm 0.001$.

The bright prompt gamma-ray emission of GRB 180618A consists of a multipeaked structure with total duration ≈0.3 s and maximum energy radiated in the MeV domain, making GRB 180618A one of the most energetic gamma-ray pulses ever detected among short-duration GRBs (i.e., flux, fluence, $E_{\rm peak}$). After the typically short and spectrally hard gamma-ray pulse, we also detect a period of weak extended gamma-ray emission below ≈100 keV, lasting ≈45 s.

We find no detectable polarization at optical bands and a rate of change of the light that initially follows a power law $F_\nu \propto t^{-\alpha}$, with index $\alpha = 0.46 \pm 0.02$. The optical emission is surprisingly short-lived, and the slow decline is replaced by a sudden drop in brightness 35 minutes post-burst, steepening to $\alpha = 4.6 \pm 0.3$. The light-curve break progressively passes from the ultraviolet to near-infrared bands. Afterwards, there is no further detection of the optical transient at the GRB 180618A coordinates.

The GRB 180618A optical counterpart presents temporal and spectral properties that do not satisfy the characteristic scalings of the synchrotron spectrum of the GRB afterglow (Sari et al. 1998)—powered by the shock of the relativistic collimated ejecta with the circumburst medium. In contrast, the fast-fading X-ray emission is consistent with a decelerating jetted outflow and with an extra emission component ≈0.5 days post-burst. This leads us to consider two distinct mechanisms powering the X-ray and unusual optical emission.

The modeling of the overall emission suggests thermal-like emission from a relativistically expanding source dominating the optical emission ≈15–60 minutes post-burst, which naturally accounts for the sharp chromatic drop of the optical emission at high-frequency wavelengths. Furthermore, the X-ray to optical emission before 15 minutes post-burst is consistent with the fast-fading jet afterglow.

We interpret the unusual spectral and temporal properties of GRB 180618A as evidence of a highly magnetized, spinning neutron star that survives for longer than $\approx 10^5$ s after the merger and spins down at a rate $L_{\rm th} \propto t^{-(2.22 \pm 0.14)}$ powering a relativistically expanding hot thermal nebula in the process. Here, we confirm that newborn millisecond magnetars can power bright emission components across the electromagnetic spectrum that remain detectable at cosmological distances: i.e., the extended soft gamma-ray emission following some short GRBs (Metzger et al. 2008; Bucciantini et al. 2012), optical plateaus at early times (Knust et al. 2017), the fast-evolving bright thermal optical emission (Yu et al. 2013; Metzger & Piro 2014), and the late-time flattening of the X-ray light curve (Metzger & Piro 2014; Gao et al. 2015). The early afterglow emission drop and the short-lived thermal optical emission may explain why such thermal emission has not been detected yet in other short GRBs with extended emission; this discovery opens a new era for searches of gravitational wave counterparts with fast-cadence surveys.

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References

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017a, ApJL, 848, L12
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017b, ApJL, 848, L13
Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, ApJS, 219, 12
Amati, L. 2006, MNRAS, 372, 233
Aptekar, R. L., Frederiks, D. D., Golenetskii, S. V., et al. 1995, SSRv, 71, 265
Arnaud, K., Dorman, B., & Gordon, C. 1999, XSPEC: An X-ray spectral fitting package, Astrophysics Source Code Library, ascl:9910.005
Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Arnold, D. M., Steele, I. A., Bates, S. D., Mottram, C. J., & Smith, R. J. 2012, Proc. SPIE, 8446, 84462J
Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, AJ, 156, 123
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Barkov, M. V., & Pozanenko, A. S. 2011, MNRAS, 417, 2161
Barrett, P. E., & Bridgman, W. T. 1999, in ASP Conf. Ser. 172, PyFITS, a FITS Module for Python, ed. D. M. Mehringer, R. L. Plante, & D. A. Roberts (San Francisco, CA: ASP), 483
Barthelmy, S. D., Barbier, L. M., Cummings, J. R., et al. 2005, SSRv, 120, 143
Behroozi, P. S., Ramirez-Ruiz, E., & Fryer, C. L. 2014, ApJ, 792, 123
Berger, E. 2010, ApJ, 722, 1946
Berger, E., Fong, W., & Chornock, R. 2013, ApJL, 774, L23
Berger, E., Price, P. A., Cenko, S. B., et al. 2005, Natur, 438, 988
Beroiz, M., Cabral, J. B., & Sanchez, B. 2020, A&C, 32, 100384
Beuermann, K., Hessman, F. V., Reinsch, K., et al. 1999, A&A, 352, L26
Beznogov, M. V., Page, D., & Ramirez-Ruiz, E. 2020, ApJ, 888, 97
Blackburn, J. K. 1995, in ASP Conf. Ser. 77, FTOOLS: A FITS Data Processing and Analysis Software Package, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes (San Francisco, CA: ASP), 367
Bloom, J. S., Frail, D. A., & Sari, R. 2001, AJ, 121, 2879
Bloom, J. S., Kulkarni, S. R., Djorgovski, S. G., et al. 1999, Natur, 401, 453
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002, AJ, 123, 1111
Bradley, L., Sipocz, B., Robitaille, T., et al. 2016, Photutils: Photometry tools, Astrophysics Source Code Library, ascl:1609.011
Breeveld, A. A., Landsman, W., Holland, S. T., et al. 2011, in AIP Conf. Proc. 1358, Gamma Ray Bursts 2010, ed. J. E. McEnery, J. L. Racusin, & N. Gehrels (Melville, NY: AIP), 373
Bucciantini, N., Metzger, B. D., Thompson, T. A., & Quataert, E. 2012, MNRAS, 419, 1537
Burrows, D. N., Hill, J. E., Nousek, J. A., et al. 2005, SSRv, 120, 165
Calderone, G., Ghirlanda, G., Ghisellini, G., et al. 2015, MNRAS, 448, 403
Campana, S., Mangano, V., Blustin, A. J., et al. 2006, Natur, 442, 1008
Chevalier, R. A., & Li, Z.-Y. 2000, ApJ, 536, 195
Clarke, D., & Neumayer, D. 2002, A&A, 383, 360
Costa, E., Frontera, F., Heise, J., et al. 1997, Natur, 387, 783
Covino, S., Wiersema, K., Fan, Y. Z., et al. 2017, NatAs, 1, 791
Cucchiara, A., Levan, A. J., Fox, D. B., et al. 2011, ApJ, 736, 7
D'Avanzo, P., Salvaterra, R., Bernardini, M. G., et al. 2014, MNRAS, 442, 2342
De Colle, F., Lu, W., Kumar, P., Ramirez-Ruiz, E., & Smoot, G. 2018, MNRAS, 478, 4553
D'Elia, V., Campana, S., D'Aì, A., et al. 2018, A&A, 619, A66
Duffell, P. C., Quataert, E., Kasen, D., & Klion, H. 2018, ApJ, 866, 3
Evans, P. A., Beardmore, A. P., Page, K. L., et al. 2009, MNRAS, 397, 1177
Fermi-LAT Collaboration, Ajello, M., Atwood, W. B., et al. 2021, NatAs, 5, 385
Fong, W., & Berger, E. 2013, ApJ, 776, 18
Fong, W., Berger, E., Margutti, R., & Zauderer, B. A. 2015, ApJ, 815, 102
Fong, W.-f., Nugent, A. E., Dong, Y., et al. 2022, arXiv:2206.01763
Fontana, A., Dunlop, J. S., Paris, D., et al. 2014, A&A, 570, A11
Fox, D. B., Frail, D. A., Price, P. A., et al. 2005, Natur, 437, 845
Fryer, C. L., Belczynski, K., Ramirez-Ruiz, E., et al. 2015, ApJ, 812, 24
Fryer, C. L., Woosley, S. E., Herant, M., & Davies, M. B. 1999, ApJ, 520, 650
Gamma-ray astronomy Group, U. o. A. H. 2014, rmfit: Forward-folding spectral analysis software, Astrophysics Source Code Library, ascl:1409.011
Gao, H., Ding, X., Wu, X.-F., Dai, Z.-G., & Zhang, B. 2015, ApJ, 807, 163
Gao, H., Ding, X., Wu, X.-F., Zhang, B., & Dai, Z.-G. 2013, ApJ, 771, 86
Gehrels, N., Ramirez-Ruiz, E., & Fox, D. B. 2009, ARA&A, 47, 567
Ghirlanda, G., Nava, L., Ghisellini, G., Celotti, A., & Firmani, C. 2009, A&A, 496, 585
Giacomazzo, B., & Perna, R. 2013, ApJL, 771, L26
Giallongo, E., Ragazzoni, R., Grazian, A., et al. 2008, A&A, 482, 349
Goldstein, A., Veres, P., Burns, E., et al. 2017, ApJL, 848, L14
Guidorzi, C., Monfardini, A., Gomboc, A., et al. 2006, PASP, 118, 288
Guiriec, S., Briggs, M. S., Connaugthon, V., et al. 2010, ApJ, 725, 225
Hamburg, R., Bissaldi, E. & Fermi GBM Team 2018, GCN, 22794, 1
Hill, J. M., Green, R. F., & Slagle, J. H. 2006, Proc. SPIE, 6267, 62670Y
Hjorth, J., Watson, D., Fynbo, J. P. U., et al. 2005, Natur, 437, 859
Høg, E., Fabricius, C., Makarov, V. V., et al. 2000, A&A, 355, L27
Hu, Y.-D., Liang, E.-W., Xi, S.-Q., et al. 2014, ApJ, 789, 145
Hunter, J. D. 2007, CSE, 9, 90
Izzo, L., de Ugarte Postigo, A., Maeda, K., et al. 2019, Natur, 565, 324
Jordana-Mitjans, N., Mundell, C. G., Kobayashi, S., et al. 2020, ApJ, 892, 97
Jordana-Mitjans, N., Mundell, C. G., Smith, R. J., et al. 2021, MNRAS, 505, 2662
Kaneko, Y., Bostancı, Z. F., Göğüş, E., & Lin, L. 2015, MNRAS, 452, 824
Kann, D. A., Klose, S., Zhang, B., et al. 2011, ApJ, 734, 96
Kaspi, V. M., & Beloborodov, A. M. 2017, ARA&A, 55, 261
Kelley, L. Z., Ramirez-Ruiz, E., Zemp, M., Diemand, J., & Mandel, I. 2010, ApJL, 725, L91
Knust, F., Greiner, J., van Eerten, H. J., et al. 2017, A&A, 607, A84
Kobayashi, S. 2000, ApJ, 545, 807
Kouveliotou, C., Meegan, C. A., Fishman, G. J., et al. 1993, ApJL, 413, L101
Krühler, T., Schady, P., Greiner, J., et al. 2011, A&A, 526, A153
LaPorte, S. J., Barthelmy, S. D., Kennea, J. A., et al. 2018, GCN, 22790, 1
Lee, W. H., & Ramirez-Ruiz, E. 2007, NJPh, 9, 17
Lee, W. H., Ramirez-Ruiz, E., & López-Cámara, D. 2009, ApJL, 699, L93
Lien, A., Sakamoto, T., Barthelmy, S. D., et al. 2016, ApJ, 829, 7
Liu, C., Zhang, Y., Li, X., et al. 2020, SCPMA, 63, 249503
MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262
Margalit, B., & Metzger, B. D. 2019, ApJL, 880, L15
Mazaeva, E., Kusakin, A., Pozanenko, A., et al. 2018, GCN, 22809, 1
Meegan, C., Lichti, G., Bhat, P. N., et al. 2009, ApJ, 702, 791
Mészáros, P., & Rees, M. J. 1997, ApJ, 476, 232
Metzger, B. D. 2019, LRR, 23, 1
Metzger, B. D., Bauswein, A., Goriely, S., & Kasen, D. 2015, MNRAS, 446, 1115
Metzger, B. D., Beniamini, P., & Giannios, D. 2018, ApJ, 857, 95
Metzger, B. D., Martínez-Pinedo, G., Darbha, S., et al. 2010, MNRAS, 406, 2650
Metzger, B. D., & Piro, A. L. 2014, MNRAS, 439, 3916
Metzger, B. D., Quataert, E., & Thompson, T. A. 2008, MNRAS, 385, 1455
Molinari, E., Vergani, S. D., Malesani, D., et al. 2007, A&A, 469, L13
Moss, M., Lien, A., Guiriec, S., Cenko, S. B., & Sakamoto, T. 2022, ApJ, 927, 157
Mösta, P., Radice, D., Haas, R., Schnetter, E., & Bernuzzi, S. 2020, ApJL, 901, L37
Mundell, C. G., Kopač, D., Arnold, D. M., et al. 2013, Natur, 504, 119
Murguia-Berthier, A., Montes, G., Ramirez-Ruiz, E., De Colle, F., & Lee, W. H. 2014, ApJL, 788, L8
Murguia-Berthier, A., Ramirez-Ruiz, E., De Colle, F., et al. 2021, ApJ, 908, 152
Murguia-Berthier, A., Ramirez-Ruiz, E., Montes, G., et al. 2017, ApJL, 835, L34
Nakar, E., & Piran, T. 2017, ApJ, 834, 28
Norris, J. P., & Bonnell, J. T. 2006, ApJ, 643, 266
Norris, J. P., Gehrels, N., & Scargle, J. D. 2010, ApJ, 717, 411
Nugent, A. E., Fong, W.-f., Dong, Y., et al. 2022, arXiv:2206.01764
O'Connor, B., Troja, E., Dichiara, S., et al. 2022, MNRAS, 515, 4890
Oechslin, R., & Janka, H. T. 2006, MNRAS, 368, 1489
Paczynski, B. 1986, ApJL, 308, L43
Perley, D. A., Metzger, B. D., Granot, J., et al. 2009, ApJ, 696, 1871
Piran, T. 1999, PhR, 314, 575
Piranomonte, S., D'Avanzo, P., Covino, S., et al. 2008, A&A, 491, 183
Planck Collaboration, Aghanim, N., Akrami, Y., et al. 2020, A&A, 641, A6
Pogge, R. 2019, rwpogge/modsCCDRed: v2.0.1, Zenodo, doi:10.5281/zenodo.2647501
Pogge, R. W., Atwood, B., Brewer, D. F., et al. 2010, Proc. SPIE, 7735, 77350A
Poolakkil, S., Preece, R., Fletcher, C., et al. 2021, ApJ, 913, 60
Poole, T. S., Breeveld, A. A., Page, M. J., et al. 2008, MNRAS, 383, 627
Racusin, J. L., Liang, E. W., Burrows, D. N., et al. 2009, ApJ, 698, 43
Ragazzoni, R., Giallongo, E., Pasian, F., et al. 2000, Proc. SPIE, 4008, 439
Ramirez-Ruiz, E., Andrews, J. J., & Schrøder, S. L. 2019, ApJL, 883, L6
Ramirez-Ruiz, E., Celotti, A., & Rees, M. J. 2002, MNRAS, 337, 1349
Rastinejad, J. C., Gompertz, B. P., Levan, A. J., et al. 2022, arXiv:2204.10864
Rees, M. J., & Meszaros, P. 1992, MNRAS, 258, 41P
Ridnaia, A., Svinkin, D., Frederiks, D., et al. 2021, NatAs, 5, 372

Roberts, L. F., Kasen, D., Lee, W. H., & Ramirez-Ruiz, E. 2011, ApJL, 736, L21
Roberts, O. J., Veres, P., Baring, M. G., et al. 2021, Natur, 589, 207
Roming, P. W. A., Kennedy, T. E., Mason, K. O., et al. 2005, SSRv, 120, 95
Rosswog, S. 2007, MNRAS Lett., 376, L48
Rosswog, S., Ramirez-Ruiz, E., & Davies, M. B. 2003, MNRAS, 345, 1077
Rowlinson, A., O'Brien, P. T., Metzger, B. D., Tanvir, N. R., & Levan, A. J. 2013, MNRAS, 430, 1061
Ruiz, M., & Shapiro, S. L. 2017, PhRvD, 96, 084063
Sakamoto, T., Barthelmy, S. D., Cummings, J. R., et al. 2018, GCN, 22796, 1
Sari, R. 1999, ApJL, 524, L43
Sari, R., & Piran, T. 1999, ApJ, 520, 641
Sari, R., Piran, T., & Halpern, J. P. 1999, ApJL, 519, L17
Sari, R., Piran, T., & Narayan, R. 1998, ApJL, 497, L17
Scargle, J. D. 1998, ApJ, 504, 405
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schmidt, G. D., Elston, R., & Lupie, O. L. 1992, AJ, 104, 1563
Sharma, V., Bhattacharya, D., Bhalerao, V., et al. 2018, GCN, 22842, 1
Siegel, M. H., LaPorte, S. J. & Swift/UVOT Team 2018, GCN, 22810, 1
Singh, K. P., Tandon, S. N., Agrawal, P. C., et al. 2014, Proc. SPIE, 9144, 91441S
Song, X.-Y., Xiong, S.-L., Zhang, S.-N., et al. 2022, ApJS, 259, 46
Steele, I. A. 2004, AN, 325, 519
Svinkin, D., Frederiks, D., Hurley, K., et al. 2021, Natur, 589, 211
Svinkin, D., Golenetskii, S., Aptekar, R., et al. 2018, GCN, 22822, 1
Tanvir, N. R., Levan, A. J., Fruchter, A. S., et al. 2013, Natur, 500, 547
Tanvir, N. R., Levan, A. J., González-Fernández, C., et al. 2017, ApJL, 848, L27
Thöne, C. C., de Ugarte Postigo, A., Fryer, C. L., et al. 2011, Natur, 480, 72
Tody, D. 1986, Proc. SPIE, 627, 733
Troja, E., Ryan, G., Piro, L., et al. 2018, NatCo, 9, 4089
Tsvetkova, A., Frederiks, D., Golenetskii, S., et al. 2017, ApJ, 850, 161
Tsvetkova, A., Frederiks, D., Svinkin, D., et al. 2021, ApJ, 908, 83
Turnshek, D. A., Bohlin, R. C., Williamson, R. L. I., et al. 1990, AJ, 99, 1243
Tyurina, N., Lipunov, V., Gorbovskoy, E., et al. 2018, GCN, 22797, 1
van Paradijs, J., Groot, P. J., Galama, T., et al. 1997, Natur, 386, 686
Villasenor, J. S., Lamb, D. Q., Ricker, G. R., et al. 2005, Natur, 437, 855
Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, NatMe, 17, 261
von Kienlin, A., Meegan, C. A., Paciesas, W. S., et al. 2020, ApJ, 893, 46
Wollaeger, R. T., Fryer, C. L., Fontes, C. J., et al. 2019, ApJ, 880, 22
Woosley, S. E. 1993, ApJ, 405, 273
Yamazaki, R., Ioka, K., & Nakamura, T. 2002, ApJL, 571, L31
Yu, Y.-W., Zhang, B., & Gao, H. 2013, ApJL, 776, L40
Zhang, B., Fan, Y. Z., Dyks, J., et al. 2006, ApJ, 642, 354
Zhang, B., & Mészáros, P. 2004, IJMPA, 19, 2385
Zhang, B., Zhang, B.-B., Virgili, F. J., et al. 2009, ApJ, 703, 1696
Zhang, B. B., Zhang, B., Sun, H., et al. 2018, NatCo, 9, 447
Zhang, H.-M., Liu, R.-Y., Zhong, S.-Q., & Wang, X.-Y. 2020, ApJL, 903, L32
Zhu, Z. P., Xu, D., Zhang, J. B., et al. 2018, GCN, 22804, 1