A tale of two mergers: constraints on kilonova detection in two short GRBs at $z \sim 0.5$


1 INTRODUCTION

The progenitors of short gamma-ray bursts (sGRBs) were long suspected to be compact binary mergers (Blinnikov et al. 1984; Paczynski 1986; Eichler et al. 1989; Narayan, Paczynski & Piran 1992), comprising either two neutron stars (NSs; Ruffert & Janka 1999; Rosswog, Ramirez-Ruiz & Davies 2003; Rosswog 2005) or an NS and a black hole (BH; Faber et al. 2006; Shibata & Taniguchi 2011). The merger remnant is either a BH (Baiotti, Giacomazzo & Rezzolla 2008; Kiuchi et al. 2009) or a massive NS (Giacomazzo & Perna 2013; Hotokezaka et al. 2013b). In either case, the merger launches a relativistic jet that produces the observed prompt gamma-ray emission (Rezzolla et al. 2011; Paschalidis, Ruiz & Shapiro 2015; Ruiz et al. 2016). The interaction of the relativistic jet with the surrounding medium produces the afterglow emission (Mészáros & Rees 1997; Sari, Piran & Narayan 1998; Wijers & Galama 1999) observed across the electromagnetic spectrum.

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ABSTRACT

We present a detailed multiwavelength analysis of two short gamma-ray bursts (sGRBs) detected by the Neil Gehrels Swift Observatory: GRB 160624A at $z = 0.483$ and GRB 200522A at $z = 0.554$. These sGRBs demonstrate very different properties in their observed emission and environment. GRB 160624A is associated with a late-type galaxy with an old stellar population ($\approx 3$ Gyr) and moderate ongoing star formation ($\approx 1 M_{\odot}$ yr$^{-1}$). Hubble and Gemini limits on optical/near-infrared emission from GRB 160624A are among the most stringent for sGRBs, leading to tight constraints on the allowed kilonova properties. In particular, we rule out any kilonova brighter than AT2017gfo, disfavouring large masses of wind ejecta ($\lesssim 0.03 M_{\odot}$). In contrast, observations of GRB 200522A uncovered a luminous ($L_{F125W} \approx 10^{42}$ erg s$^{-1}$ at 2.3 d) and red ($r - H \approx 1.3$ mag) counterpart. The red colour can be explained either by bright kilonova emission powered by the radioactive decay of a large amount of wind ejecta ($0.03 M_{\odot} \lesssim M \lesssim 0.1 M_{\odot}$) or moderate extinction, $E(B-V) \approx 0.1$–0.2 mag, along the line of sight. The location of this sGRB in the inner regions of a young ($\approx 0.1$ Gyr) star-forming ($\approx 2$–$6 M_{\odot}$ yr$^{-1}$) galaxy and the limited sampling of its counterpart do not allow us to rule out dust effects as contributing, at least in part, to the red colour.

Key words: stars: jets – neutron star mergers – gamma-ray bursts.
The connection between sGRBs and NS mergers was consolidated by the joint detection of the gravitational wave (GW) event GW170817 (Abbott et al. 2017) and the short GRB 170817A (Goldstein et al. 2017; Savchenko et al. 2017). These were followed by the luminous (\( L_{\text{bol}} \approx 10^{42} \text{ erg s}^{-1} \)) kilonova AT2017gfo (Andreoni et al. 2017; Arcavi et al. 2017; Chornock et al. 2017; Coulter et al. 2017; Covino et al. 2017; Cowperthwaite et al. 2017; Drout et al. 2017; Evans et al. 2017; Kasliwal et al. 2017a; Lipunov et al. 2017; Nicholl et al. 2017; Pian et al. 2017; Shappee et al. 2017; Smartt et al. 2017; Tanvir et al. 2017; Troja et al. 2017; Utsumi et al. 2017; Valenti et al. 2017). AT2017gfo was initially characterized by a blue thermal spectrum, which progressively shifted to redder colours and displayed broad undulations typical of fast-moving ejecta (e.g. Watson et al. 2019).

Kilonova emission following an NS–NS merger originates from the radioactive decay of freshly synthesized r-process elements in neutron-rich matter surrounding the remnant compact object (Li & Paczyński 1998; Metzger et al. 2010; Barnes & Kasen 2013; Tanaka & Hotokezaka 2013; Grossman et al. 2014; Kasen et al. 2017). Kilonovae are hallmarked by ‘blue’ thermal emission within a day of merger (e.g. AT2017gfo) that fades and gives way to the ‘red’ and near-infrared (NIR) emission, persisting for roughly a week post-merger. Neutron-rich material (electron fraction \( Y_e < 0.25 \)) composed of high-opacity lanthanides produces the red component, while the blue component results from ejecta material with higher electron fraction (Barnes & Kasen 2013; Kasen, Fernández & Metzger 2015; Kasen et al. 2017; Tanaka et al. 2017; Wollaeger et al. 2018, 2019; Even et al. 2020; Fontes et al. 2020; Korobkin et al. 2020). Dynamical ejecta, tidally stripped from the approaching NS(s), primarily contributes to the red component. In addition, a portion of the matter that congregates in an accretion disc surrounding the disc, with a longer lived high-mass NS remnant increasing the disc support a wide range of electron fractions, enhancing either the red or the blue component (Kasen et al. 2015). The range of electron fractions of ejecta predicted from models of disc winds varies with the implementation of the neutrino transport (Miller et al. 2019).

Although kilonovae are usually described as near-isotropic, they exhibit viewing-angle-dependent variations based on ejecta morphology (Korobkin et al. 2020) and lanthanide curtaining effects (Kasen et al. 2015). Observations of AT2017gfo were possible because of the particular geometry of GW170817, whose relativistic jet was misaligned with respect to our line of sight (Lazzati et al. 2017; Hubble Space Telescope (HST) imaging to search for a counterpart with unusually red colours was found for the short GRB 070724A (\( t - K_s \approx 1.9 \)) and, in both cases, attributed to dust effects at the GRB site. The rapid time scales and high luminosity (\( 10^{42} \text{ erg s}^{-1} \)) of these two sources did not match the predictions of a radioactive-powered kilonova, although they could fit within the expected range for a magnetar-powered kilonova (Yu, Zhang & Gao 2013).

Densely sampled multicolour observations, extending to the NIR range, proved to be essential in the identification of the kilonova candidates GRB 130603B (Tanvir et al. 2013) and GRB 160821B (Lamb et al. 2019b; Troja et al. 2019b). The counterpart of GRB 130603B was identified within the spiral arm of its bright host galaxy. The source appeared unusually red, in part due to significant presence of dust along the sightline (\( AV \approx 1 \text{ mag} \)), and was seen to evolve over the course of time, from \( R - H \approx 1.7 \pm 0.15 \) at about 14 h to \( R - H > 2.5 \) at about 9 d. GRB 160821B was instead located in the outskirts of a nearby spiral galaxy, and its counterpart was also identified as unusually red (\( V - K \approx 1.9 \)). A detailed modelling of the X-ray and radio afterglow was able to disentangle the presence of an additional emission component in the optical and NIR data, slightly less luminous than AT2017gfo and with similar time scales and colour evolution (Lamb et al. 2019b; Troja et al. 2019b). For both GRB110330B and GRB 160821B, a good spectral sampling over multiple epochs was a fundamental ingredient to distinguish the kilonova candidate from the underlying bright afterglow.

In addition to these candidate kilonovae, there are a number of claimed kilonova detections based on an optical excess, e.g. GRB 050709 (Jin et al. 2016), GRB 060614 (Yang et al. 2015), GRB 070809 (Jin et al. 2020), GRB 080503 (Perley et al. 2009), and GRB 150101B (Troja et al. 2018). The situation for these events is less clear due to the lack of deep NIR observations, critical to distinguish kilonova emission from standard afterglow.

The number of sGRBs with well-characterized afterglows and sensitive NIR observations is still restricted to a handful of cases (see e.g. Gompertz et al. 2018; Rossi et al. 2020). In this work, we continue filling this observational gap by presenting a detailed multiwavelength study of two distant sGRBs: GRB 160624A at \( z = 0.483 \) and GRB 200522A at \( z = 0.554 \). We complement the early Swift data with deep Chandra observations in order to characterize the afterglow temporal evolution up to late times, and use deep Gemini and Hubble Space Telescope (HST) imaging to search for kilonova emission.

The paper is organized as follows. In Section 2, we present the observations and data analysis for GRBs 160624A and 200522A. In Section 3, we describe the methods applied for our afterglow and kilonova modelling, as well as the galaxy spectral energy distribution (SED) fitting procedure. The results are presented in Section 4, and our conclusions in Section 5. For each GRB, we provide the time of observations relative to the Burst Alert Telescope (BAT) trigger time, \( T_0 \), in the observer frame. All magnitudes are presented in the AB system. We adopt the standard \( \Lambda \)-CDM cosmology with parameters \( H_0 = 67.4, \Omega_M = 0.315, \) and \( \Omega_L = 0.685 \) (Planck Collaboration VI 2018). All confidence intervals are at the 1σ level and upper limits at the 3σ level, unless otherwise stated. Throughout the paper, we adopt the convention \( F_\nu \propto t^{-\alpha} \nu^{-\beta} \).
Figure 1. BAT mask-weighted light curve (15–350 keV) of GRB 160624A with 16 ms binning. The shaded vertical region marks the $T_{90}$ duration.

2 OBSERVATIONS AND ANALYSIS

2.1 GRB 160624A

2.1.1 Gamma-ray observations

GRB 160624A triggered the Swift BAT (Barthelmy et al. 2005) at 2016 June 24 11:27:01 UT (D’Ai et al. 2016), hereafter referred to as $T_0$ for this GRB. The burst was single pulsed with duration $T_{90} = 0.2 \pm 0.1$ s and fluence $f_p = (4.0 \pm 0.9) \times 10^{-5}$ erg cm$^{-2}$ (15–150 keV). We performed a search of the BAT light curve (Fig. 1) for extended emission (EE; Norris & Bonnell 2006) following the discussion of the host association, see Section 4.1.3. This was also detected by the Fermi Gamma-ray Burst Monitor (GBM; Meegan et al. 2009). The time-averaged GBM spectrum, from $T_0 - 0.06$ s to $T_0 + 0.2$, is well fit by a power law with an exponential cut-off with low-energy spectral index $\alpha = -0.4 \pm 0.3$ and a peak energy $E_p = 800 \pm 400$ keV (Hamburg & von Kienlin 2016). Based on this model, the observed fluence is $f_p = (5.2 \pm 0.5) \times 10^{-4}$ erg cm$^{-2}$ (10–100 keV), corresponding to an isotropic equivalent gamma-ray energy $E_{\gamma,\text{iso}} = (4.7 \pm 1.5) \times 10^{50}$ erg (1 keV–10 MeV; rest frame) at a redshift $z = 0.483$ (see Sections 2.1.4 and 4.1.3).

2.1.2 X-ray observations

The Swift X-ray Telescope (XRT; Burrows et al. 2005) began observing at $T_0 + 59$ s and localized the X-ray afterglow at a position in RA, Dec. $(J2000) = 22^\circ 00' 46'' 21', +29^\circ 38' 37'' 8$ with an accuracy of 1.7 arcsec [90 per cent confidence level (CL); Evans et al. 2007, 2009]. Data were collected in window timing (WT) mode during the first 150 s and, as the source rapidly increased in brightness, in photon counting (PC) mode. A deeper observation was carried out at $T_0 + 8.5$ d (PT: Troja; ObsId 18021) by the Chandra X-ray Observatory (ACIS-S3), but no X-ray counterpart was detected. We describe the observed temporal decay (Fig. 7) with a broken power law, consisting of two segments with $F_\gamma \propto t^{-\alpha_i}$. The initial decay is $\alpha_1 = 0.6 \pm 0.3$ which steepens to $\alpha_2 = 4.0 \pm 0.3$ after $t_{\text{break}} \sim 140$ s.

We model the XRT spectra with XSPEC v12.1.1 (Arnaud 1996) by minimizing the Cash statistics (Cash 1979). The Galactic hydrogen column density was fixed to the value $N_H = 9.14 \times 10^{20}$ cm$^{-2}$ (Willingale et al. 2013). We determine that the time-averaged X-ray spectrum is well described (C-stat = 249 for 336 dof) by an absorbed power-law model with photon index $\Gamma = 1.76 \pm 0.15$ and intrinsic hydrogen column density $N_H,\text{int} = (2.8^{+1.7}_{-1.0}) \times 10^{21}$ cm$^{-2}$ (required at the 5σ level). This yields a time-averaged unabsorbed flux $F_X = (3.5 \pm 0.3) \times 10^{-10}$ flux for WT mode data ($T_0 + 58$ to $T_0 + 150$ s), and (2.1 $\pm 0.2) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (0.3-10 keV) for PC mode data ($T_0 + 150$ to $T_0 + 600$ s). The unabsorbed energy conversion factor (ECF) is $6.7 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ for WT mode data and $6.9 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ for PC mode.

The Chandra data were reprocessed using the CIAO 4.12 data reduction package with CALDB Version 4.9.0, and filtered to the energy range 0.5–7 keV. We corrected the native Chandra astrometry by aligning the image with the Gaia Data Release 2 (Gaia Collaboration 2018). We utilized CIAO tools to extract a count rate within the XRT error region (1.7 arcsec source aperture radius), utilizing nearby source-free regions to estimate the background. We detect zero counts in the source region with an estimated background of 0.6 counts s$^{-1}$ for WT mode and 6.9 in the 0.3–10 keV band using the best-fitting spectral parameters. The derived X-ray fluxes are reported in Table 1.

2.1.3 Optical/NIR imaging

The ultra-violet optical telescope (UVOT; Roming et al. 2005) on-board Swift began observations at $T_0 + 77$ s, although no optical afterglow is identified within the XRT position to $m \geq 21.8$ AB mag (de Pasquale & D’Ai 2016). The field was imaged with the Gemini MultiObject Spectrograph (GMOS; Hook et al. 2004) on the 8.1-m Gemini North telescope (PI: Cucchiara) starting at $T_0 + 31$ min. An initial 180-s r-band exposure led to the identification of a candidate host galaxy within the XRT error region (SDSS J220046.14 + 293839.3; Cucchiara & Levan 2016); for further discussion of the host association, see Section 4.1.3. This was followed by deeper observations (900 and 1440 s, respectively) at $T_0 + 1$ h and $T_0 + 1$ d. Seeing during the observations was $\sim 0.5$ arcsec with mean airmass 1.1 and 1.0, respectively. We retrieved the data from the Gemini archive. Data were analysed following standard CCD reduction techniques and using the Gemini IRAF package.

At later times, we performed two epochs of observations (PI: Trojan; ObsId 14357) with the HST Advanced Camera for Surveys (ACS) wide-field camera (WFC) and wide-field camera 3 (WFC3) in infrared (IR). See Table 1 for a log of observations. The HST data were processed using the sndrizpipe pipeline, which uses standard procedures within the DrizzlePac package, in order to align, drizzle, and combine exposures. The final image pixel scale was 0.09 arcsec pix$^{-1}$ for WFC3 (i.e. F125W and F160W) and 0.04 arcsec pix$^{-1}$ for ACS (i.e. F606W).

1https://www.swift.ac.uk/xrt_curves/

2IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation (NSF).

3https://github.com/srodney/sndrizpipe
We identify no candidate counterpart within the XRT localization in either Gemini or HST images. Since the XRT localization overlaps significantly with the candidate host galaxy (see Fig. 2), we performed image subtraction between epochs using the High Order Transform of Psf ANd Template Subtraction code (HOT-PANTS; Becker 2015) to search for transient sources embedded within the host galaxy’s light. Due to the short time delay between Gemini epochs, our analysis may not reveal a slowly evolving transient. We therefore verified our results using the late (T0 + 8.2 d) HST/F606W image as the template. Furthermore, as kilonovae can dominate at either early or late times, depending on the composition of the ejecta, we performed image subtraction between the HST epochs using each epoch as a template image. No significant residual source was uncovered in either the Gemini or HST difference images at any epoch, as shown in Fig. 2.

In order to determine the upper limit on a transient source in these images, we injected artificial point-like sources within the XRT position and performed image subtraction to detect any residual signal. Gemini magnitudes were calibrated to nearby Sloan Digital Sky Survey Data Release 12 (SDSS; Fukugita et al. 1996) stars. HST magnitude zero-points were determined with the photometry keywords obtained from the HST image headers, and were corrected with the STScI tabulated encircled energy fractions. The upper limits derived for the field are presented in Table 1. Upper limits within the galaxy’s light are shallower by 0.3−0.5 mag.

Finally, we obtained imaging of the candidate host galaxy on May 20, 2018 (T0 + 1059 d) with the Large Monolithic Imager.
Figure 2. Left: RGB image of the field of GRB 160624A using the three HST filters: $F606W =$ blue, $F125W =$ green, and $F160W =$ red. The XRT localization (1.7 arcsec) is shown in magenta. In the top left, a chip gap from the $F606W$ observation is marginally visible. Centre: Deep images of the position of GRB 160624A in the Gemini/r-band at $T_0 + 1 \text{ h}$ (top) and HST/$F606W$ filter at $T_0 + 8.2 \text{ d}$ (centre). The bottom panel shows the difference image between Gemini and HST (template) using HOTPARTS. There are no significant residuals within the enhanced XRT position. The images are smoothed for display purposes. Right: HST images of GRB 160624A in the $F125W$ filter taken at $T_0 + 4.3 \text{ d}$ (top) and $T_0 + 8.3 \text{ d}$ (centre). The difference image is shown in the bottom panel.

Table 2. Observations of the host galaxy of GRB 160624A. Magnitudes are not corrected for Galactic extinction, $E(B−V) = 0.06$ mag, in the direction of the burst.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Filter</th>
<th>Exp. (s)</th>
<th>AB Mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDT/LMI</td>
<td>$g$</td>
<td>180</td>
<td>23.31 ± 0.09</td>
</tr>
<tr>
<td>HST/ACS/WFC</td>
<td>$F606W$</td>
<td>1960</td>
<td>22.147 ± 0.014</td>
</tr>
<tr>
<td>Gemini/GMOS</td>
<td>$r$</td>
<td>1440</td>
<td>22.18 ± 0.02</td>
</tr>
<tr>
<td>LDT/LMI</td>
<td>$r$</td>
<td>180</td>
<td>22.16 ± 0.08</td>
</tr>
<tr>
<td>LDT/LMI</td>
<td>$i$</td>
<td>180</td>
<td>21.66 ± 0.08</td>
</tr>
<tr>
<td>LDT/LMI</td>
<td>$z$</td>
<td>360</td>
<td>21.47 ± 0.08</td>
</tr>
<tr>
<td>Gemini/NIRI</td>
<td>$Y$</td>
<td>540</td>
<td>21.42 ± 0.15</td>
</tr>
<tr>
<td>HST/WFC3</td>
<td>$F125W$</td>
<td>2411</td>
<td>20.842 ± 0.004</td>
</tr>
<tr>
<td>HST/WFC3</td>
<td>$F160W$</td>
<td>2411</td>
<td>20.566 ± 0.004</td>
</tr>
<tr>
<td>Gemini/NIRI</td>
<td>$K_s$</td>
<td>180</td>
<td>20.32 ± 0.08</td>
</tr>
</tbody>
</table>

(LMI) mounted on the 4.3-m Lowell Discovery Telescope (LDT) in Happy Jack, AZ. Observations were taken in the griz filters, with seeing ∼1.65 arcsec at a mean airmass of ∼1.3. We applied standard procedures for reduction and calibration of these images. We obtain the galaxy apparent magnitude in each filter using the SExtractor $\text{MAG}_\text{AUTO}$ parameter, which utilizes Kron elliptical apertures (Bertin & Arnouts 1996). Magnitudes were calibrated to nearby SDSS stars, and reported in Table 2. Near-infrared imaging in the $YK$ bands was carried out on 2020 July 25 with the Near-Infrared Imager (NIRI; Hodapp et al. 2003) on the 8-m Gemini North telescope. Data were reduced using standard procedures within the DRAGONS package. The photometry was calibrated to nearby sources from the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; Chambers et al. 2016) and Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) for the $V$- and $K_s$-band images, respectively. We used the offsets from Blanton & Roweis (2007) to convert 2MASS Vega magnitudes to the AB system.

2.1.4 Optical spectroscopy

A spectrum of the candidate host galaxy was obtained using Gemini/GMOS (PI: Cucchiara) starting at $T_0 + 46 \text{ min}$. GMOS was configured with the R400 grating at a central wavelength of 600 nm. We reduced and analysed the data using the Gemini IRAF package (v. 1.3.2 running in CASA v4.7.2). We followed the same procedure described in Ricci et al. (2020) using galaxies 3C 48 and J2203 as primary and phase calibrators, respectively. We do not detect a radio transient coincident with the enhanced XRT position with a flux density upper limit <18 $\mu$Jy.

2.1.5 Radio observations

Radio observations were carried out with the Karl J. Jansky Very Large Array (JVLA) starting at $T_0 + 1 \text{ d}$ (PI: Berger; project code: 15A-235) with the array in the B configuration. The observations were taken in the X band, with a central frequency 10 GHz and a bandwidth of 2 GHz. The time on source was 47 min. Data were downloaded from the National Radio Astronomical Observatory online archive, and processed locally with the JVLA CASA pipeline v1.3.2 running in CASA v4.7.2. We followed the same procedure described in Ricci et al. (2020) using galaxies 3C 48 and J2203 + 3145 as primary and phase calibrators, respectively. We do not detect a radio transient coincident with the enhanced XRT position with a flux density upper limit <18 $\mu$Jy.
and we derive an isotropic equivalent gamma-ray energy of $E_{\gamma, \text{iso}} = (7.3 \pm 1.0) \times 10^{59} \text{erg} (15 - 150 \text{keV}; \text{rest frame})$ for a redshift $z = 0.554$ (see Sections 2.2.4 and 4.2.6).

2.2.2 X-ray observations

Swift/XRT observations were delayed due to the South Atlantic Anomaly, and began at $T_0 + 406$ s (Evans et al. 2020). The X-ray counterpart was detected at RA, Dec. $(J2000) = 00^\circ22^\prime43.7'' -01^\circ 16^\prime 59.4''$ arcsec with an accuracy of 2.2 arcsec (90 per cent CL).\(^3\) XRT follow-up observations lasted 3 d for a total exposure of 17.5 ks in PC mode. We performed two ToO observations (PI: Troja; ObsIds 22456, 22457, and 23282) with Chandra/ACIS-S in order to track the late-time evolution of the X-ray light curve. During the first epoch ($T_0 + 5.6$ d), we detect the X-ray afterglow at RA, Dec. $(J2000) = 00^\circ22^\prime43.7'' -01^\circ 16^\prime 57.5''$ with accuracy 0.5 arcsec, consistent with the XRT enhanced position. A second bright X-ray source lies $\sim 10.4$ arcsec from the GRB position, and is coincident with the known quasar SDSS J002243.61-001707.8 at redshift $z = 1.44862 \pm 0.00079$ (Krawczyn et al. 2013). Due to their proximity, the two sources are not resolved in the XRT images and both contribute to the observed X-ray flux.

Analysis of the Swift and Chandra data was performed using the methods described in Section 2.1.2. We use our Chandra observations to characterize the nearby quasar, and estimate its contribution to the measured Swift/XRT flux. Using XSPEC, we derive a photon index $\Gamma = 1.53 \pm 0.14$ (C-stat 162 for 156 dof). This yields a flux $F_X = (6.6 \pm 0.6) \times 10^{-14} \text{erg cm}^{-2} \text{s}^{-1}$ (0.3–10 keV). To constrain the impact of this second source on the XRT observations, we folded the quasar spectrum with the XRT response function to obtain the expected count rate with Swift/XRT, $(1.5 \pm 0.2) \times 10^{-3}$ cts s$^{-1}$. We subtract this mean count rate from all XRT observations, although the quasar contribution is only significant at late (> 0.3 d) times.

The time-averaged XRT/PC mode spectrum from $T_0 + 400$ s to $T_0 + 17$ ks is best fit (C-stat = 65 for 73 dof) by an absorbed power law with photon index $\Gamma = 1.45 \pm 0.18$. We fix the Galactic hydrogen column density to $N_{\text{HI}} = 2.9 \times 10^{20} \text{cm}^{-2}$ (Willingale et al. 2013), and include an intrinsic absorption component at the candidate host galaxy’s redshift, $z = 0.554$. Our fit sets an upper limit $N_{\text{HI, \text{abs}}} \leq 7.4 \times 10^{21} \text{cm}^{-2}$ (3$\sigma$). This yields a time-averaged unabsorbed flux $F_X = (1.2 \pm 0.2) \times 10^{-12} \text{erg cm}^{-2} \text{s}^{-1}$, and an ECF of $5.2 \times 10^{-11} \text{erg cm}^{-2} \text{cts}^{-1}$.

In our first Chandra observation at $T_0 + 5.6$ d, the afterglow count rate is $(6.8^{+1.4}_{-1.3}) \times 10^{-4}$ cts s$^{-1}$ (0.5–7 keV). Using the best-fitting XRT spectrum, this corresponds to a flux $(1.3^{+0.5}_{-0.4}) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (0.3–10 keV). In the second observation ($T_0 + 23.9$ d), we detect two photons at the GRB position with an estimated background of 0.3 counts yielding a 3$\sigma$ upper limit $< 1.6 \times 10^{-4}$ cts s$^{-1}$ (Kraft et al. 1991). This corresponds to an unabsorbed flux $< 3.0 \times 10^{-15} \text{erg cm}^{-2} \text{s}^{-1}$ (0.3–10 keV). The X-ray fluxes from Swift and Chandra are reported in Table 3.

2.2.3 Optical/NIR imaging

The Swift/UVOT began settled observations in the $wh$ filter at $T_0 + 448$ s (Kuon et al. 2020). Subsequent observations were performed in all optical and UV filters. There was no source detected within the enhanced XRT position. The observations were analysed

\(^4\)https://swift.gsfc.nasa.gov/results/batgrbcat/

\(^5\)https://www.swift.ac.uk/xrt_positions/

Figure 3. Gemini North GMOS spectrum of the host galaxy of GRB 160624A at $z = 0.4833 \pm 0.0004$. The spectrum has been smoothed with a Gaussian kernel, presented in purple, and the error spectrum is shown in black. Gemini/r-band and LDT/i-band photometry are shown in blue. Telluric absorption regions are marked by the blue bands, and the black region at $\sim 6710 \text{Å}$ is a chip gap. The positions of detected emission lines are indicated by the black-dashed lines. We do not detect the [O III], 4959 line, but demonstrate its location for completeness.

Figure 4. BAT mask-weighted light curve (15–350 keV) of GRB 200522A with 16 ms binning. Precursor emission is visible $\sim 0.25$ s before the BAT trigger. The shaded vertical region marks the $T_0$ duration.

2.2 GRB 200522A

2.2.1 Gamma-ray observations

Swift/BAT was triggered by GRB 200522A on May 22, 2020 at 11:41:34 UT (Evans et al. 2020), hereafter $T_0$ for this GRB. The BAT light curve, shown in Fig. 4, is multipeaked with duration $T_{90} = 0.62 \pm 0.08$ s. A precursor (Troja, Rosswog & Gehrels 2010) is visible at $T_0 - 0.25$ s. We find no evidence for EE, and derive an upper limit $< 2.2 \times 10^{-2} \text{erg cm}^{-2} (15-150 \text{keV})$ between $T_0 + 2$ s and $T_0 + 100$ s.

The BAT GRB Catalogue\(^4\) reports that the time-averaged spectrum, from $T_0 - 0.2$ to $T_0 + 0.7$ s, is fit by a power law with photon index $1.45 \pm 0.17 (\chi^2 = 39$ for 57 dof). For this model, the observed fluence is $f_{\nu} = (1.1 \pm 0.1) \times 10^{-7} \text{erg cm}^{-2} (15-150 \text{keV})$.
X-ray fluxes were corrected for Galactic absorption by Indebetouw et al. (2005) and repeated in O'Connor & Troja (2020a). Aperture photometry was performed on the residual source within the optical/NIR counterpart of GRB 200522A, as reported in O'Connor et al. (2020b).}

We obtained a spectrum of the putative host galaxy using GMOS on 2020 July 17. Data were reduced following our work, we adopt instead the results derived using the single epoch spectrum. The identification of a counterpart is complicated by the presence of a bright galaxy. Image subtraction, using astrodrizzle package, was obtained at T_0 + 3.1 d. A last epoch at T_0 + 9.1 d serves as a template for image subtraction. The identification of a counterpart is complicated by the presence of a bright galaxy. Image subtraction, using HOTPAINTS, between the second (T_0 + 3.1 d) and third (T_0 + 9.1 d) epochs finds a weak (≈3σ) residual source within the Chandra localization. By performing aperture photometry on the difference image we estimate a magnitude of r = 26.0 ± 0.4 AB, calibrated against nearby SDSS stars.

NIR imaging was carried out with the HST/WFC3 using the F125W and F160W filters at three epochs (PI: Berger; ObsID 15964): T_0 + 3.5, T_0 + 16.3, and T_0 + 55.2 d. The data were processed using astrodrizzle to a final pixel scale of 0.06 arcsec pix^−1. Image subtraction, using HOTPAINTS, between the first (T_0 + 3.5 d) and third (T_0 + 55.2 d) epoch uncovers a significant residual source in both filters, at a location consistent with the optical and X-ray positions (see Fig. 5). The absolute position of the NIR transient is RA, Dec. (J2000) = 00°22′43.737, −0°16′57.481 with a 1σ uncertainty of 0.07 arcsec (tied to SDSS DR12). We interpret this source as the optical/NIR counterpart of GRB 200522A, as reported in O’Connor et al. (2020b). Aperture photometry was performed on the residual image and calibrated using the tabulated zero-points. The magnitudes are listed in Table 3. There are no significant residuals detected at the afterglow location in the F125W difference image between the second (T_0 + 16.3 d) and third epochs. Following the procedure outlined in Section 2.1.3, we inject artificial point sources to determine an upper limit F125W > 27.2 AB mag at the afterglow position.

A independent analysis of the HST data was recently reported by Fong et al. (2020), confirming our detection of the optical/NIR counterpart. The analysis of Fong et al. (2020) reports a source brighter by ≈0.4 mag in the F125W filter, which we can reproduce by using a different template image derived by combining the two epochs at T_0 + 16 and 55 d using the astrodrizzle package. In our work, we adopt instead the results derived using the single epoch at T_0 + 55 d, available for both the F160W and F125W filters, as small variations in the nearby galaxy’s nucleus may affect the photometry and the measured colour. We caution that our error bars do not include a systematic uncertainty accounting for possible variability of the galaxy’s nucleus. However, we verified that all our conclusions also hold for the alternative result of a slightly brighter transient (see Section 4.2.1).

Late-time optical and NIR images were acquired to characterize the host galaxy’s properties. Observations were carried out in the u/giz filters with the LDT/LMI on 2020 July 30 and in the YK filters with Gemini/NIRI on 2020 July 17. Data were reduced following the same procedures described in Section 2.1.3, and photometry was calibrated using nearby sources from SDSS and the United Kingdom Infrared Telescope Infrared Deep Sky Survey (Lawrence et al. 2007). The results are listed in Table 4.

<table>
<thead>
<tr>
<th>Start date (UTC)</th>
<th>∆T (d)</th>
<th>Telescope</th>
<th>Instrument</th>
<th>Exposure (s)</th>
<th>AB Mag</th>
<th>Flux density (∙µJy)</th>
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</thead>
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<tr>
<td>2020-05-22 11:49:02</td>
<td>0.005</td>
<td>Swift</td>
<td>XRT</td>
<td>233</td>
<td>46 ± 10</td>
<td>0.34 ± 0.08</td>
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<tr>
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<td>0.045</td>
<td>Swift</td>
<td>XRT</td>
<td>494</td>
<td>17 ± 5</td>
<td>0.13 ± 0.04</td>
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<tr>
<td>2020-05-22 12:54:57</td>
<td>0.051</td>
<td>Swift</td>
<td>XRT</td>
<td>875</td>
<td>19 ± 4</td>
<td>0.14 ± 0.03</td>
</tr>
<tr>
<td>2020-05-22 14:41:21</td>
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<td>Swift</td>
<td>XRT</td>
<td>2113</td>
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<td>0.031 ± 0.009</td>
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<tr>
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<tr>
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<td>XRT</td>
<td>3984</td>
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<tr>
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<td>2.6</td>
<td>Swift</td>
<td>XRT</td>
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<td>&lt;8.1 × 10^{-3}</td>
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<tr>
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<td>ACIS-S3</td>
<td>14890</td>
<td>0.31_{-0.10}^{+0.14} (9.4 ± 2.9) × 10^{-4}</td>
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<td>ACIS-S3</td>
<td>57150</td>
<td>&lt;0.03</td>
<td>&lt;2.2 × 10^{-4}</td>
</tr>
</tbody>
</table>

Note: Optical/NIR fluxes were corrected for Galactic extinction due to interstellar reddening E(B − V) = 0.02 mag (Schlafly & Finkbeiner 2011) using the extinction law by Fitzpatrick (1999) and Indebetouw et al. (2005). X-ray fluxes were corrected for Galactic absorption N_H = 2.9 × 10^{20} cm^{-2} (Willingale et al. 2013), and converted into flux densities at 1 keV using photon index Γ = 1.45.
respectively. This yields a redshift $z = 0.5541 \pm 0.0003$, in agreement with our preliminary estimate (Dichiara, O’Connor & Troja 2020b). Line properties were derived through the methods outlined in Section 2.1.4.

### 3 METHODS

#### 3.1 Afterglow modelling

We model the observed afterglows within the standard fireball model (Mezcua & Rees 1997; Sari et al. 1998; Wijers & Galama 1999; Granot & Sari 2002), described by a set of five parameters: the isotropic-equivalent kinetic energy $E_0$, the circumburst density $n_0$, the fraction of energy in magnetic fields $\varepsilon_B$ and in electrons $\varepsilon_e$, and the slope $p$ of the electron energy distribution $N(E) \propto E^{-p}$. We assume that the environment surrounding the binary merger has a uniform density profile, consistent with the interstellar medium. Three more parameters account for the outflow’s collimated geometry: the jet core width $\theta_c$, the observer’s viewing angle $\theta_v$, and the jet’s angular profile. We apply two angular profiles: (i) a uniform (tophat) jet profile with $\theta_v = 0$ and (ii) a Gaussian function in angle from the core described by $E(\theta) = E_0 \exp(-\theta^2/(2\theta_w^2))$ for $\theta \leq \theta_w$, where $\theta_w$ is the truncation angle of the Gaussian wings. The beaming corrected kinetic energy, $E_j$, is given by $E_j = E_0(1 - \cos \theta_v) \approx E_0 \theta_c^2 / 2$ for
a top-hat jet and $E_f \approx E_0\theta_c^2[1 - \exp(-\theta_c^2/2\theta^2)]$ for a Gaussian angular profile. We include the effect of intrinsic dust extinction assuming a Fitzpatrick (1999) reddening law parametrized by $R_V = A_V/E(B-V) = 3.1$.

We utilize a Bayesian fitting method in conjunction with the afterglowpy software, described in Ryan et al. (2020), to determine the GRB jet parameters. We apply the emcee (version 2.2.1; Foreman-Mackey et al. 2013) PYTHON package for Markov Chain Monte Carlo (MCMC) analysis. The independent priors for each parameter were uniform for $E(B-V) = [0, 1]$, $\theta_c = [0, \pi/4]$ and $p = [2, 5]$, and log-uniform for $\log E_0 = [48, 55]$, $\log n_0 = [-6, 2]$, $\log \varepsilon_B = [-6, -0.5]$, and $\log \varepsilon_e = [-6, -0.5]$. We have restricted $\varepsilon_e$, $\varepsilon_B < 1/3$, as without this requirement both $\varepsilon_e$ and $\varepsilon_B$ approach unphysical values of unity. For the Gaussian jet profile, we adopt the uniform priors $\theta_v = [0, \pi/4]$ and $\theta_w = [0.01, \min(\pi/4, 12\theta_v)]$. Each fit used an ensemble MCMC sampler that employed 300 walkers for 100 000 steps with an initial burn-in phase of 25 000 steps, yielding $2.25 \times 10^7$ posterior samples. Additional details of the methods can be found in Troja et al. (2018), Piro et al. (2019), and Ryan et al. (2020).

We compare models by evaluating their predictive power with the Widely Applicable Information Criterion (WAIC; also known as the Watanabe-Akaike Information Criterion; Watanabe 2010). The WAIC score is an estimate of a model’s expected log predictive density ($elpd$): roughly the probability that a new set of observations would be described by the model’s fit to the original data. A model with a high $elpd$ (and WAIC score) produces accurate, constraining predictions. A model with a low $elpd$ (and WAIC score) produces predictions that are inaccurate or not constraining. This naturally penalizes overfitting: overfit models typically show wide variability away from the observations that leads to poor predictive power and a low WAIC score. The WAIC score estimates the $elpd$ by averaging the likelihood of each observation over the entire posterior probability distribution. As a model comparison tool, this incorporates the uncertainties in the model parameters (unlike the reduced $\chi^2$ or the Akaike Information Criterion) and does not require the posterior probability distribution to be normal (unlike the Deviance Information Criterion).

We compute the WAIC score following Gelman, Hwang & Vehtari (2013) using the recommended $p_{WAIC}^{N}$ as an effective number of parameters. The WAIC score is computed at every data point and the total WAIC score is the sum of these contributions. In order to compare the WAIC score of two different models, we compute the standard error, $\sigma_{SE}$, of their difference, $\Delta WAIC_{elpd}$ (Vehtari, Gelman & Gabry 2015). One model is favoured over another if it has a higher overall WAIC score and the difference between the WAIC scores $\Delta WAIC_{elpd}$ is significantly larger than its uncertainty $\sigma_{SE}$. As $\sigma_{SE}$ can underestimate the true standard deviation of $\Delta WAIC_{elpd}$ by up to a factor of 2 (Bengio & Grandvalet 2004), we report a conservative significance on the WAIC score difference using $\sigma_{\Delta WAIC} \approx 2\sigma_{SE}$.

3.2 Kilonova modelling

3.2.1 Empirical constraints

Optical and infrared observations constrain the properties of possible kilonovae associated with each GRB. In the case of GRB 160624A, no optical or NIR counterpart was detected and kilonova models are directly constrained by our photometric upper limits. GRB 200522A presents instead a complex phenomenology, characterized by a bright X-ray afterglow and an optical/NIR counterpart with a red colour ($r-H \approx 1.3$, Table 3). Such red colour could be the result of dust along the sightline or the telltale signature of a kilonova. In order to constrain the contribution of the latter, we add to our afterglow fit an additional thermal component.

Korobkin et al. (2020) demonstrated that a simple analytical fit to kilonova light curves can lead to order of magnitude uncertainties in the inferred ejected mass, depending on the unknown geometry of the system. We therefore use a different approach which combines empirical constraints and detailed numerical simulations. At the time of our optical/NIR observations (~3.5 d), the kilonova component is roughly described by a simple blackbody. Therefore, we use a parametrized blackbody component, included in addition to the standard forward shock (FS) emission, to determine the possible thermal contribution from a kilonova. The range of fluxes allowed by this fit is then compared to an extensive suite of simulated kilonova light curves (Section 3.2.2) in order to derive the ejecta properties. The blackbody component is described by two parameters, its temperature $T$ and emission radius $R$, with uniform priors between [0–8000 K] and [0–5 $\times 10^{15}$ cm], respectively. The upper limit on radius is chosen to prevent a superluminal expansion velocity. Since our optical and NIR data are nearly coeval, we assume that there is negligible temporal and spectral evolution between observations.

3.2.2 Constraints on kilonova ejection properties

We compare optical and infrared constraints to simulated kilonova light curves of varying input parameters, consistent with a wide range of plausible ejecta morphologies, compositions, masses, and velocities. For this study, we use a grid of two-component kilonova models from the LANL group (Wollaeger et al., in preparation). This data set was previously used in Thakur et al. (2020) to constrain ejecta parameters for GW190814. Simulations include time-dependent spectra, as early as three hours post-merger, which are subsequently converted to light curves for various filters. We simulate kilonovae with SuperNu (Wollaeger & van Rossum 2014), a multidimensional, multigroup Monte Carlo transport code, which has previously been used in a wide range of kilonova studies (Wollaeger et al. 2018, 2019; Even et al. 2020; Korobkin et al. 2020; Thakur et al. 2020). Our simulations rely on the WinNet nucleosynthesis network (Winteler et al. 2012) to simulate heating from radioactive decay in addition to the latest LANL opacity database (Fontes et al. 2020). We consider a full set of lanthanide opacities, while uranium acts as a proxy for all actinide opacities.

We model kilonovae with two ejecta components: dynamical ejecta including heavy r-process elements and wind ejecta emanating from the resultant accretion disc surrounding the remnant compact object. We consider two disparate wind models, representing ejecta with either high-latitude ($Y_e = 0.37$) or mid-latitude ($Y_e = 0.27$) compositions, both having negligible lanthanide contributions. Wind ejecta assumes either a spherical or ‘peanut-shaped’ morphology, while dynamical ejecta remains toroidal. These models correspond to the TS and TP morphologic profiles in Korobkin et al. (2020).

The grid of models includes a range of mass and velocity parameters, in addition to two morphologies and two wind compositions. Both the dynamical and wind ejecta span five possible masses: 0.001, 0.003, 0.01, 0.03, and 0.1 $M_\odot$. We ascribe one of three possible velocity distributions to both the dynamical and wind ejecta components, with median velocities of either 0.05c, 0.15c, or 0.3c,
corresponding to maximum ejecta velocities of 0.1c, 0.3c, and 0.6c. The grid spans the anticipated range of ejecta properties expected from numerical simulations and observations of GW170817 (Korobkin et al. 2012; Kasen et al. 2017; Coté et al. 2018; Metzger 2019; Krüger & Foucart 2020). Each multidimensional simulation computes kilonova emission for 54 different polar viewing angles. Our axisymmetric simulations report spectra and light curves for separate viewing angles, distributed uniformly in sine of the polar angle from edge-on, on-axis viewing angles (0°) to edge-off (180°). Including all viewing angles and kilonova properties, we have 48 600 different sets of time-dependent spectra to compare to optical and infrared observations.

We limit our simulation grid to kilonovae observed on-axis, when considering optical and infrared observations in conjunction with a GRB, observed with viewing angle θv ≈ 0. Our on-axis simulations consider viewing angles from 0° to 15.64°. We then compare the 900 on-axis kilonova simulations to optical and NIR observations. We restrict plausible kilonova parameters to the range of simulated light curves consistent with observations, either light curves dimmer than the measured upper limits (see Section 4.1.2) or light curves residing in the range of inferred kilonova emission from analytic fits (see Section 4.2.5).

3.3 Galaxy SED modelling

We compare the observed photometry to a range of synthetic SEDs generated with the flexible stellar population synthesis code (Conroy, Gunn & White 2009). We adopt the same models used in Mendel et al. (2014) to describe SDSS galaxies: a Chabrier (2003) initial mass function with integration limits of 0.08 and 120 M⊙ (imf_type = 1); an intrinsic dust attenuation using the extinction law of Calzetti et al. (2000, dust_type = 2); a smoothly declining star formation history characterized by an e-folding time scale, τ. We apply a delayed-τ model (zFH = 4) for the star formation history. The contribution of nebular emission is computed using the photoionization code CLOUDY (Ferland et al. 2013) and added to the spectrum. These choices result in five free parameters: the total stellar mass formed, M*, the age tage of the galaxy, the e-folding time scale τ, the intrinsic reddening E(B − V), and the metallicity Z. From these parameters, we derive the stellar mass, Me = ξ M*, where ξ is the ratio of the surviving stellar mass to the formed mass, and the star formation rate, SFR, computed as

\[
\text{SFR}(t_{\text{age}}) = M_e \frac{1}{\tau^2 \gamma(2, t_{\text{age}}/\tau)} t_{\text{age}} e^{-t_{\text{age}}/\tau},
\]

where \(\gamma(a, x)\) is the lower incomplete gamma function. The mass-weighted stellar age, t_m, is then derived as

\[
t_m = t_{\text{age}} - \int_0^{t_{\text{age}}} t \times \text{SFR}(t) dt = \int_0^{t_m} \text{SFR}(t) dt.
\]

We sampled the posterior probability density function of these parameters by using the affine-invariant ensemble MCMC sampler implemented in the EMCEE package (Foreman-Mackey et al. 2013). We adopted uniform priors in log t_{\text{age}}, log τ, log Z, E(B − V) over the same parameter range as Mendel et al. (2014, cf. their table 2), and ran each fit with 128 walkers for 4096 steps, dropping the initial 100 000 steps as an initial burn-in phase and generating \(\approx 400 000\) posterior samples. The MCMC walkers were initialized near the maximum of the posterior, calculated through optimization of the likelihood function. Fits were performed with the PROSPECTOR code (Johnson et al. 2019), customized to use our chosen cosmology.

4 RESULTS

GRB 160624A and GRB 200522A are two short-duration GRBs located at a similar distance (\(z = 0.483\) and 0.554, respectively), which display very different properties in their observed emission. GRB 160624A is characterized by a bright, short-lived X-ray afterglow that is no longer detected after a few hundreds seconds. The faint afterglow and lack of any optical/NIR counterpart allow for stringent constraints on kilonova emission from the deep Gemini and HST observations (see Section 4.1). GRB 200522A displays instead a bright and long-lived counterpart. The red colour of its optical/NIR emission (\(r = H \approx 1.3\) mag) represents tantalizing evidence for a kilonova, but its interpretation is complicated by the uncertain contribution of the standard afterglow. The burst location, close to the galaxy’s centre, and evidence for active star formation suggest that extinction along the sightline could also contribute to the observed colour (see Section 4.2).

4.1 GRB 160624A

4.1.1 Afterglow properties

As shown in Fig. 7, GRB 160624A displays a bright and rapidly fading X-ray afterglow. This feature is common among sGRBs and is often interpreted as long-lived activity of the central engine (e.g. Rowlinson et al. 2013). No evidence for a standard FS component is found by deep optical and X-ray follow-up observations. At early times (<2h), this event is characterized by the deepest available optical limits for a sGRB (see also, e.g. Sakamoto et al. 2013; Fong et al. 2015). These observations would have detected nearly all the known sGRB optical afterglows, with the only exception of GRB 090515, and place some of the tightest constraints on the optical luminosity of sGRBs (Fig. 8).

Using afterglowpy, we explore the range of afterglow parameters allowed by the broad-band upper limits. We fixed \(p = 2.2\), and left the other parameters (\(E_0, n_0, \epsilon_B, \epsilon_e\)) free to vary. Although low density (\(\approx 10^{-3} \text{ cm}^{-3}\)) solutions are favoured, \(\sim 15\) per cent of the allowed models are consistent with \(n_0 \gtrsim 1 \text{ cm}^{-3}\). The faintness of the afterglow therefore does not necessarily imply a rarefied environment.
Figure 8. Optical upper limits (the black triangles) or detections (the blue circles) in the $r$ band for sGRBs at their time of first observation, measured since the GRB trigger. The three early Gemini/GMOS $r$-band upper limits for GRB 160624A are shown (the red triangles) in comparison to the rest of the population of sGRBs with measured redshift. The measurements are corrected for Galactic extinction (Schlafly & Finkbeiner 2011).

Our Chandra observation sets an upper limit to the X-ray luminosity $L_X \lesssim 1.1 \times 10^{42} \text{ erg s}^{-1} (0.3-10 \text{ keV})$ at $T_0 + 5.9 \text{ d}$ (rest frame). This limit is compared in Fig. 7 to the late-time X-ray excess detected for short GRBs 080503 (Perley et al. 2009) and 130603B (Fong et al. 2014), which is often attributed to a long-lived and highly magnetized NS remnant (e.g. Gao et al. 2013; Metzger & Piro 2014). The interaction of the magnetar spin-down radiation with the merger ejecta could power a bright X-ray transient on time scales of a few days after the merger. The predicted peak luminosity is $10^{43} - 10^{45} \text{ erg s}^{-1}$ with a decay following the temporal behaviour of the spin-down emission, $L_{\text{sd}} \propto t^{-2}$. In order to be consistent with these models, our non-detection of X-rays favours a newborn NS with a large magnetic field $B \gtrsim 10^{15} \text{ G}$ for ejecta masses $M_e \gtrsim 10^{-2} \text{ M}_\odot$ (Metzger & Piro 2014). Alternatively, the early steep decay of the X-ray afterglow may mark the NS collapse to a BH.

4.1.2 Kilonova constraints

We constrain parameters of a potential kilonova associated with GRB 160624A by comparing optical and infrared upper limits to 900 on-axis kilonova simulations, introduced in Section 3.2.2. We only consider observations after $T_0 + 0.125 \text{ d}$ (rest frame), as spectra are not computed prior to this time. Using spectra simulated at various times, we convert kilonova emission to observer frame light curves in Gemini/$r$-band, $HST/F606W$, $HST/F125W$, and $HST/F160W$ filters.

The four panels of Fig. 9 show the range of simulated light curves in each filter. The coloured regions indicate the range of light curves eliminated by upper limits, while the grey regions indicate light curves consistent with observations. AT2017gfo light curves are included for comparison, and show that $HST/F125W$...
and HST/F160W observations may be sensitive to AT2017gfo-like kilonovae. The AT2017gfo photometry was compiled from Arcavi et al. (2017), Cowperthwaite et al. (2017), Drout et al. (2017), Kasliwal et al. (2017a), Pian et al. (2017), Shappee et al. (2017), Smartt et al. (2017), Tanvir et al. (2017), Troja et al. (2017), Utsumi et al. (2017), and Valenti et al. (2017).

Our HST/F160W observations provide the most stringent constraints on the range of plausible light curves, disallowing 30 per cent of on-axis light curves from the simulation grid. Individually, the Gemini-r-band upper limit at ~1 d (observer frame) eliminated 12 per cent of light curves, while the earlier HST/F606W and HST/F125W observations eliminate 8 per cent and 23 per cent of light curves, respectively. The HST/F125W upper limit at ~8 d post-merger (observer frame) and the HST/F160W upper limit at ~9 d post-merger (observer frame) only provide redundant constraints, eliminating light curves otherwise constrained by the four aforementioned upper limits. The HST/F606W upper limit at ~8 d post-merger (observer frame) places no constraint on the range of kilonova parameters. In total, 31 per cent of simulated on-axis kilonovae are ruled out by the observational constraints on GRB 160624A.

Fig. 10 indicates the fraction of simulated light curves consistent with observations for all combinations of dynamical and wind ejecta mass. Constraints indicate that high ejecta masses are strongly disfavoured, with 86 per cent of simulations with 0.2 M⊙ total ejecta mass (0.1 M⊙ of dynamical ejecta + 0.1 M⊙ wind ejecta) excluded by observational constraints. High wind ejecta masses (>0.1 M⊙) are disfavoured with over 80 per cent of models disallowed by the upper limits. Wind mass dictates light-curve behaviour at lower (optical) wavelengths, while dynamical ejecta mass dominates at higher (NIR) wavelengths. However, due to the cosmological distance of this GRB, our reddest filter, HST/F160W, corresponds only to the rest frame y band. As a result, our observations can only weakly constrain the dynamical ejecta with 53 per cent of 0.1 M⊙ models consistent with the data. Nearly all models with ejecta masses below 0.04 M⊙ are consistent with the data.

For high ejecta masses, we are able to place strong constraints on the range of ejecta velocities. For example, light curves with wind ejecta masses of 0.1 M⊙ and low velocities (≤0.15c) are strongly disfavoured. Similarly, models with wind ejecta 0.03 M⊙ and low velocity (0.05c) are predominately disfavoured, while the majority of high-mass models (with velocity 0.3c) are consistent with the data. Velocity constraints are primarily due to the timing of our observations. For constant mass, higher velocities result in earlier and brighter peak emission (see e.g. Thakur et al. 2020). As a result, many high-velocity models have dimmed by the time of these observations and cannot be ruled out by the upper limits, while several low wind velocity models coincide with observations and are thus ruled out.

4.1.3 Environment

The best localization for GRB 160624A is its XRT position with an error radius of 1.7 arcsec (90 per cent CL). This position intercepts a bright galaxy (Fig. 2), which we identified as the GRB host galaxy. Using the XRT localization, the maximum projected physical offset from this host galaxy is ≤ 21.5 kpc (90 per cent CL). Using the GALFIT package (Peng et al. 2002), we fit this galaxy with a Sersic profile of index n = 1 and derive an optical half-light radius R_e ≈ 1.1 arcsec (6.8 kpc). Therefore, the maximum host-normalized offset is R/R_e ≲ 3.2.

Following Bloom, Kulkarni & Djorgovski (2002), we calculate the chance probability Pcc using the R-band number counts from Beckwith et al. (2006) for optical observations, and the H-band number counts from Metcalfe et al. (2006) for NIR observations. We derive Pcc =0.03 using the observed magnitude r = 22.18 ± 0.02, and Pcc =0.02 using HST/F160W = 20.566 ± 0.004 (see Table 2). We searched the field for other candidate host galaxies. We identify three bright SDSS galaxies at offsets of 21, 22.4, and 39 arcsec with Pcc ≈ 0.2, 0.5, and 0.9, respectively. There are a few dim extended objects, uncovered in the HST observations, at moderate offsets ≥ 4 arcsec with Pcc ≥ 0.5. Additionally, a faint source with F160W = 26.2 ± 0.3 mag is observed within the XRT position. Due to its faint nature, we cannot determine whether this is a star or a galaxy. In the latter case, the source’s probability of chance coincidence is Pcc ≈ 0.7. Therefore, the association of GRB 160624A with the bright galaxy SDSS J220046.14 + 293839.3 remains the most likely.

We characterize the putative host galaxy’s properties by modelling the optical and NIR SED (Table 2) as outlined in Section 3.3. The result is shown in Fig. 11. The best-fitting parameters describing the galaxy are an intrinsic extinction E(B − V) = 0.13 ± 0.06 mag, a near solar metallicity Z/Z⊙ = 0.9 ± 0.3, an e-folding time τ = 1.4^{+0.6}_{−0.2} Gyr, a stellar mass log(M/M⊙) = 9.97^{+0.06}_{−0.07}, an old stellar population t_n = 2.8^{+1.0}_{−0.9} Gyr, and a moderate SFR = 1.6^{+0.6}_{−0.4} M⊙ yr$^{-1}$.

We compare these results to those inferred using standard emission line diagnostics. Assuming Hα/Hβ = 2.86 (Osterbrock 1989), we derive a SFR(Hα) = 1.2 ± 0.2 M⊙ yr$^{-1}$; Kennicutt (1998). This is consistent with the SFR derived using the [O II] line luminosity, SFR([O II]) = 1.7 ± 0.7 M⊙ yr$^{-1}$ (Kennicutt 1998), and only slightly lower than the SFR from SED modelling, suggesting that most of the star formation activity is not obscured by dust. Overall, these results are in keeping with the properties of sGRB host galaxies.

4.2 GRB 200522A

4.2.1 Afterglow properties

Before introducing our broad-band modelling, we start with some basic considerations on the afterglow properties. In X-rays, the
observed spectral index $\beta_X = 0.45 \pm 0.18$ suggests that $v_m < v_X < v_e$, otherwise $p \lesssim 1.5$. Here, $v_m$ is the injection frequency of electrons, and $v_e$ is the cooling frequency. A consistent spectral index (at $\sim 2\sigma$) is derived from the optical and NIR observations, $\beta_{\text{OIR}} = 1.1 \pm 0.3$, suggesting the optical/NIR and X-ray data could lie on the same spectral segment. We therefore fit the broad-band SED (X-ray/optical/NIR) at $t_{\text{GRB}} + 3.5$ d with an absorbed power-law model \texttt{reddeninthebabs (zdust (powerlaw))} within \texttt{XSPEC}. We fix the Galactic column density $N_H = 2.9 \times 10^{20}$ cm$^{-2}$, and $R_V = A_V/E(B-V) = 3.1$ (Rieke & Lebofsky 1985). As there is no X-ray observation at this time, we re-scale the flux of the early-time XRT spectrum to the predicted value at 3.5 d. This fit yields $\beta_{\text{XO}} = 0.77 \pm 0.05$ and $E(B-V) = 0.12^{+0.12}_{-0.08}$ mag ($\chi^2 = 71$ for 78 dof), consistent with $v_m < v_{\text{IR}} < v_X < v_e$ and $p = 2.54 \pm 0.10$. However, for this value the predicted temporal slope, $\alpha = 3p/2 \approx 1.16$, is steeper than the slope, $\alpha_X = 0.84 \pm 0.04$, measured in X-rays.

In GRB afterglows, it is not uncommon to observe a shallow temporal decay, not accounted for by the simple FS model. In general, this behaviour is observed in the early ($<1000$ s) light curve, whereas later observations tend to be consistent with standard closure relations. Indeed, in this case too, we find that, by excluding the early X-ray data, the temporal slope steepens to $\alpha_X = 1.04 \pm 0.08$ in agreement with the FS predictions. Therefore, in our modelling we only consider the late ($>1000$ s) X-ray data, as earlier epochs could be affected by complex factors (e.g. energy injection, jet structure) not included in the basic FS model.

In the radio band, the afterglow is detected at a nearly constant level in the two early epochs (at $t_{\text{GRB}} + 0.23$ and $t_{\text{GRB}} + 2.2$ d), and then seen to fade (see Fong et al. 2020). In the simple FS model, the radio emission is expected to either rise as $v^{1.5}$, if below the spectral peak ($v < v_m$), or decay as $v^{-0.125}$ when above the peak ($v > v_m$). The observed flattening can therefore be explained only if the synchrotron peak crosses the radio band between 0.1 and 2 d.

Alternatively, the flat radio light curve could reveal the presence of a reverse shock (RS) component contributing at early times (Fong et al. 2020), as observed in other bright short GRBs (e.g. Soderberg et al. 2006; Becerra et al. 2019; Lamb et al. 2019b; Troja et al. 2019b). Both scenarios are considered in our modelling.

We include an additional systematic uncertainty in the radio data to account for the scattering and scintillation of radio wavelengths due to interstellar scintillation (ISS). We adopt the ‘NE2001’ model (Cordes & Lazio 2002), which yields a scattering measure $SM = 1.9 \times 10^{-4}$ kpc m$^{-200}$ and a transition frequency $v_0 \approx 8$ GHz for the direction of GRB 200522A. Radio observations at $v_{\text{GRB}} < v_0$ can be effected by strong scattering when the angular extent of the GRB jet is $\theta_{\text{GRB}} < \theta_{\text{F0}} \approx 1$ mas. In our afterglow modelling, we find that this condition, $\theta_{\text{GRB}} < \theta_{\text{F0}}$, is satisfied at $\lesssim 2.5$ d. Therefore, we include a 30 percent systematic uncertainty, added in quadrature with the statistical uncertainty, to account for the effects of ISS.

Using an MCMC Bayesian fitting approach, outlined in Section 3.1, we explore four different models to describe the broadband afterglow of GRB 200522A from radio to X-rays. By assuming a top-hat jet, we consider (i) an FS with intrinsic extinction from the host galaxy (hereafter denoted by FS+Ext), (ii) an FS with an additional blackbody component (FS + BB, see Section 3.2.1), and (iii) an FS and simple blackbody with the addition of intrinsic extinction (FS+BB+Ext). For a structured jet, we consider (iv) a Gaussian profile, standard FS emission, and intrinsic extinction (Gauss+FS + Ext). The results are tabulated in Tables 5 and A1 (available in the online version). We discuss the results of these fits for the models with only FS emission in Section 4.2.2 and models with an additional BB component in Section 4.2.3. A comparison of the WAIC score difference between these models is presented in Section 4.2.4. Lastly, in Section 4.2.5, we explore the consistency of the predicted flux from our BB models with detailed kilonova simulations (Section 3.2.2).
We note that Mode III appears with high significance only when the first radio detection at \( <1000 \) s without requiring additional energy injection. However, unlike the top-hat jet model, the Gaussian angular profile does not provide a tight constraint on the jet’s opening angle, \( \theta_c \). Although the ratio \( \theta_{\text{jet}}/\theta_c \) is better constrained to \( \theta_{\text{jet}}/\theta_c \leq 2.3 \).

Both these jet models underestimate the radio detections at \( T_0 + 0.23 \) d and at \( T_0 + 2.2 \) d. This could be attributed to synchrotron self-Compton (SSC) and Klein–Nishina effects (e.g. Jacobi, Benamini \& van der Horst 2020), not included in our code, and/or to a bright RS component.

### 4.2.3 Afterglow models including a blackbody component

In this section, we present the multimodal solutions for our afterglow models that include a simple blackbody component, with (FS + BB + Ext) and without extinction (FS + BB). The fit to the broad-band data set for each model is shown in Fig. 13, and the parameter values are presented in Table A1. Marginalized posterior distributions for each parameter are displayed in Figs A3 and A4 for the FS + BB and FS + BB + Ext models, respectively (all supplementary figures and tables are available in the online version of the manuscript). Each model exhibits three modes, referred to as Mode I, Mode II, and Mode III, which are presented individually in Table 5. Mode I is characterized by a late (\( t > 10 \) d) radio peak and no jet-break, Mode II shows an earlier peak (2 d < \( t < 5 \) d) and requires a jet-break, and Mode III also finds a jet-break and describes the first and second radio detections without an RS component due to an early radio peak (0.3–0.5 d). Although the MCMC algorithm cannot distinguish one of these modes as providing a better description of the data, we disfavour Mode I based on the extremely low circumburst density (\( n \approx 10^{-5} \) cm\(^{-3} \)) and the phenomenology of sGRB afterglows. Such late radio peaks have not been observed in sGRBs, and Mode I is likely an artefact of the poorly constrained late-time radio data set. We therefore favour either Mode II or Mode III as a more likely description of the jet parameters. Both of them constrain the jet-opening angle to \( \theta_{\text{jet}} \approx 0.10 \) rad (6\( \circ \)).

When including extinction, the only difference in the fit is in the temperature \( T \) and radius \( R \) of the blackbody component: the model without dust extinction requires a cooler thermal component (\( T \approx 4000 \) K) to match the optical data. A higher temperature (\( T \gtrsim 6500 \) K), as predicted, e.g. in the magnetar-boosted model (Fong et al. 2020), tends to overpredict the optical flux, unless dust extinction contributes to attenuate the observed emission.

### 4.2.4 Model comparison

We perform a comparison of the models applied in this work using their WAIC scores, described in Section 3.1 (see also Troja et al. 2020; Cunningham et al. 2020). We note that the WAIC analysis is not applicable to individual modes within the models, and that we only compare the overall model fits presented in Table A1.

For the four models considered, the difference between the WAIC scores is not significant enough to statistically favour any of them. In particular, the addition of a blackbody to the FS fit is not required by the data. We find that the WAIC score of the FS + BB + Ext model...
4.2.5 Kilonova constraints

We use the simple blackbody component, described in Section 3.2, to constrain the contribution of a possible kilonova to the observed NIR emission. The blackbody luminosity lies in the range $L_{\text{F125W}} \approx (7-19) \times 10^{41} \text{ erg s}^{-1}$ and $L_{\text{F160W}} \approx (7-15) \times 10^{41} \text{ erg s}^{-1}$ (observer frame). Although the constraint on a thermal contribution at (observer frame) optical wavelengths has a greater uncertainty $L_r \approx (2-22) \times 10^{41} \text{ erg s}^{-1}$. These values are somewhat larger than observed from other candidate kilonovae and AT2017gfo, which are $\approx (1-3) \times 10^{41} \text{ erg s}^{-1}$ at similar times.

We utilize our MCMC algorithm to determine a posterior distribution on the temperature $T$ and radius $R$ of the blackbody (Table 5), only marginally (at the 1.2σ level) improves over the FS + Ext model.

The most significant difference in WAIC score ($\Delta \text{WAIC}_{\text{elpd}} = -62 \pm 40$) is between the FS + Ext and Gauss + FS + Ext models. A larger WAIC score implies a better description of the data (see Section 3.1), and therefore the FS + Ext model is marginally preferred at the $\approx 1.4\sigma$ level.

Our findings do not depend on the details of the data analysis, which yield slightly different magnitudes for the NIR counterpart (see Section 2.2.3). In particular, we verified that, by using the values presented by Fong et al. (2020), our results are unchanged. There is no significant difference between the posterior distributions of the fit parameters, and the WAIC score comparison continues to not favour any particular model fit.

**Figure 12.** Broad-band light curve of GRB 200522A compared to the standard forward shock with intrinsic extinction scenario for two angular profiles, tophat (Top: model FS + Ext) and Gaussian (Bottom: model Gauss + FS + Ext). The shaded regions mark the 1σ uncertainty in the model. The hollow circles mark data excluded from the fit (see Section 4.2.1). 3σ upper limits are denoted by the downward triangles.

**Figure 13.** Same as in Fig. 12, but for the forward shock model with a blackbody component (Top: model FS + BB) and with intrinsic extinction (Bottom: model FS + BB + Ext). The shaded regions display only the afterglow contribution to the flux. Multiple solutions are consistent with the data: a late radio peak at $\gtrsim 10$ d (Mode I), a radio peak between 2 and 5 d (Mode II), and an early radio peak at 0.3–0.8 d (Mode III; the dotted line). The excess emission ($HST/F125W$) is compared to a simulated kilonova light curve (the maroon-dashed line) with properties: $M_{\text{ej}, d} = 0.001M_\odot$, $v_{\text{ej}, d} = 0.3c$, $M_{\text{ej}, w} = 0.1 M_\odot$, and $v_{\text{ej}, w} = 0.15c$. 

The most significant difference in WAIC score ($\Delta \text{WAIC}_{\text{elpd}} = -62 \pm 40$) is between the FS + Ext and Gauss + FS + Ext models. A larger WAIC score implies a better description of the data (see Section 3.1), and therefore the FS + Ext model is marginally preferred at the $\approx 1.4\sigma$ level.

Our findings do not depend on the details of the data analysis, which yield slightly different magnitudes for the NIR counterpart (see Section 2.2.3). In particular, we verified that, by using the values presented by Fong et al. (2020), our results are unchanged. There is no significant difference between the posterior distributions of the fit parameters, and the WAIC score comparison continues to not favour any particular model fit.
from which we compute a distribution for the emitted flux from the blackbody in each filter. The flux posterior distributions are then compared to the LANL suite of kilonova simulations (see Section 3.2.2) in order to estimate the ejecta masses and velocities required to reproduce the observations. Fig. 14 presents five kilonova light curves (the solid lines) consistent with the blackbody flux estimated in the FS + BB + Ext model. They lie within the inner 50 per cent credible interval of both HST/F125W and HST/F160W posteriors. As the FS contribution likely dominates at optical wavelengths, we do not require consistent light curves to reside in the 50 per cent credible interval of the Gemini/r-band constraint.

These results indicate that any thermal component, as constrained from our broad-band modelling, agrees with a radioactively powered kilonova emission. The five consistent light curves span a wide range of dynamical ejecta masses (0.001 M⊙ ≤ M_{ej,d} ≤ 0.1 M⊙), but share many other properties, including a wind ejecta mass of M_{ej,w} = 0.1 M⊙, wind ejecta velocity of v_{ej,w} = 0.15 c, dynamical ejecta velocity of v_{ej,d} = 0.3 c, and spherical wind morphology. These observations provide stronger constraints on the wind ejecta mass as the F125W and F160W filters probe rest frame optical wavelengths. We emphasize that these five light curves represent only a small subset of kilonova parameters capable of reproducing the flux posteriors.

This result differs from the findings of Fong et al. (2020), who argue for an additional power source (e.g. an enhanced radioactive heating rate or a magnetar) to boost the kilonova luminosity to values higher than AT2017gfo. This difference arises despite comparable predictions for the NIR thermal emission, with their predicted luminosities (L_{F125W} ≈ (9.5–12.3) × 10^{41} erg s^{-1} and L_{F160W} ≈ (8.9–11.4) × 10^{41} erg s^{-1}) fully encapsulated within our luminosity posterior distribution. Our multidimensional kilonova models can reproduce this range of values by incorporating the same physics adopted to model AT2017gfo (Evans et al. 2017; Tanvir et al. 2017; Troja et al. 2017; Wollaeger et al. 2018), including a thermalizable heating rate of \approx 10^{10} erg g^{-1} s^{-1} at t = 1 d. In addition, they capture the multicomponent character of kilonova ejecta, leading to an enhancement of the emission via photon reprocessing (Kawaguchi, Shibata & Tanaka 2020). This is illustrated in Fig. 14, which compares our models (the solid lines), produced by a spherical wind component girdled with a toroidal lanthanide-rich ejecta, with the emission produced by a single-component spherical morphology (the dashed line), with properties (M_{ej} = 0.1 M⊙, v_{ej,w} = 0.15 c, Y_{e} = 0.27) similar to the models used in Fong et al. (2020). The addition of the toroidal belt produces a \approx 1 mag enhancement of the HST/F160W flux compared to the single-component model. This is attributed to the reprocessing of photons emitted from the spherical wind by the high-opacity ejecta. Photons absorbed by the toroidal component preferentially diffuse towards the polar regions, and are re-emitted at redder wavelengths. The flux enhancement at optical wavelengths is instead negligible. This effect is more prominent in events viewed along the polar axis, such as GRB 200522A.

4.2.6 Environment

GRB 200522A is located within a bright galaxy, SDSS J002243.71–001657.5, at z = 0.554. The projected offset from the galaxy’s nucleus is R = 0.16 ± 0.04 arcsec (1.07 ± 0.27 kpc); in the bottom 15 per cent of the sGRB offset distribution (Fong & Berger 2013). Using GALFIT, we derive a projected half-light radius R_e = 0.60 ± 0.02 arcsec, corresponding to 4.0 ± 0.1 kpc, and a normalized offset of R/R_e = 0.27 ± 0.07. The chance alignment between the GRB and the galaxy is small: we determine P_{cc} = 0.002 using the r-band magnitude, and P_{cc} = 0.003 using the F160W filter. Both the GRB offset and the galaxy’s angular size contribute to determine this value (Bloom et al. 2002). As shown in Fig. 5, there are two nearby red galaxies seen at projected angular offsets of 2.5 and 3.9 arcsec with F160W ≃ 23.5 and 20.8 AB mag, respectively. The probability of chance coincidence is P_{cc} = 0.11 and 0.05, respectively. Therefore, we consider SDSS J002243.71–001657.5 to be the likely host galaxy of GRB 200522A.

We determine the physical properties of the galaxy using the methods described in Section 3.3. The resulting best-fitting model is shown in Fig. 15. We find an integrated extinction E(B−V) = 0.02 ± 0.01 mag, a metallicity Z_{⊙}/Z_G = 1.3^{+0.16}_{−0.25}, an e-folding time \tau = 0.13^{+0.07}_{−0.03} Gyr, a stellar mass log (M_*/M_{⊙}) = 9.44 ± 0.02, a young stellar population t_m = 0.35^{+0.08}_{−0.04} Gyr, and an SFR = 2.00 ± 0.12 M_{⊙} yr^{-1}. These values are broadly consistent with those inferred by Fong et al. (2020), although they derive a slightly higher stellar mass. The stellar mass and age derived here are on the low end of the distributions for sGRB host galaxies, but are not unique to the population (Leibler & Berger 2010).

Moreover, we perform standard emission line diagnostics on the spectrum described in Section 2.2.4. The line flux ratio Hα/Hβ = 0.25 ± 0.11 does not provide a strong constraint on the intrinsic extinction E(B−V). Fong et al. (2020) infer negligible extinction, however, based on their reported line ratio Hα/Hβ = 2.9 ± 0.9, we derive E(B−V) < 1.3 mag (3σ) which does not rule out the presence of moderate extinction along the GRB line of sight. The dominant emission lines imply significant on-going star formation. We derive a SFR([OII]) = 5.4 ± 1.4 M_{⊙} yr^{-1} under the assumption Hα/Hβ = 2.86, and SFR([OII]) = 7.3 ± 1.9 M_{⊙} yr^{-1} using the [OII] line luminosity (Kennicutt 1998).

Figure 14. Simulated kilonova light curves consistent with the blackbody flux posterior distribution in the HST/F160W filter. The box indicates the inner 50 per cent credible interval, while the whisker spans the inner 90 per cent credible interval of the posterior distribution. The black line within the box corresponds to the median value. The solid lines correspond to on-axis emission from a two-component model with a spherical wind ejecta girdled by a toroidal belt of lanthanide-rich dynamical ejecta. For comparison, the dashed line shows a single-component spherical morphology with identical properties of the wind ejecta (M_{ej} = 0.1 M⊙, v_{ej,w} = 0.15 c, Y_{e} = 0.27).
5 CONCLUSIONS

We have presented an analysis of the multiwavelength data sets for two sGRBs at $z \sim 0.5$: GRB 160624A at $z = 0.483$ and GRB 200522A at $z = 0.554$. These two events demonstrate the wide range of diversity displayed by sGRBs in terms of both their emission and environment. We utilize the broad-band data sets for these two events to constrain the presence of kilonova emission arising after the compact binary merger.

Gemini and HST observations of GRB 160624A place some of the deepest limits on both optical and NIR emission from a short GRB. For this event, we find that the bright short-lived X-ray counterpart is likely related to long-lasting central engine activity, whereas emission from the FS is not detected. Because of the negligible afterglow contribution, we can robustly constrain emission from a possible kilonova. By comparing our limits to a large suite of detailed simulations, we derive a total ejecta mass $\lesssim 0.1 M_\odot$, favouring wind ejecta masses $M_{\text{ej},w} \lesssim 0.03 M_\odot$. Any kilonova brighter than AT2017gfo ($\sim 30$ per cent of the simulated sample) can be excluded by our observations.

A late-time Chandra observation places a deep upper limit on the X-ray emission ($L_X \lesssim 1.1 \times 10^{42} \text{erg s}^{-1}$), which we use to constrain the presence of a long-lived magnetar. Radiation from the magnetar nebula could ionize the low-opacity wind ejecta on a time scale of a few days/weeks (Metzger & Piro 2014), allowing for X-rays from the central engine to escape. The lack of X-ray detection at $T_0 + 5.9$ d (rest frame) implies a magnetar with a strong magnetic field ($\gtrsim 10^{15} \text{G}$) and a large mass of ejecta ($\gtrsim 10^{-2} M_\odot$). However, this amount of ejecta, when re-energized by the magnetar’s spin-down emission, should also produce a luminous optical and infrared signal detectable with both Gemini and HST. Therefore, our multiwavelength data set disfavours a stable magnetar remnant for GRB 160624A.

Very different is the phenomenology of GRB 200522A, which has a long-lived X-ray emission, largely consistent with standard FS models, and a bright NIR counterpart. Its unusual red colour ($r - H \approx 1.3$) at a rest frame time $\sim 2.3$ d is suggestive of a kilonova, although the inferred luminosity of $L_{\text{F125W}} \approx (7 - 19) \times 10^{41} \text{erg s}^{-1}$ is above the typical range observed in other candidate kilonovae (Tanvir et al. 2013; Yang et al. 2015; Ascenzi et al. 2019; Troja et al. 2019b). The identification of a kilonova is complicated by the bright and long-lived afterglow contribution, as well as by the limited colour information available for this event. Our thorough modelling of the multiwavelength data set finds that a standard FS model represents a good description of the X-ray, optical, and NIR data set provided that a modest amount of extinction, $E(B - V) \sim 0.1 - 0.2$ mag, is present along the GRB sightline. This value is not at odds with the negligible extinction from galaxy’s SED modelling, which is integrated over the whole galaxy and may not be representative of the GRB sightline, as found in other short GRBs (e.g. GRB 111117A; Sakamoto et al. 2013; Selsing et al. 2018). A moderate extinction is consistent with the constraints from optical spectroscopy, $E(B - V) \lesssim 1.3$ mag. From X-ray spectroscopy, we derive a similar upper bound of $E(B - V) \lesssim 1.1$ mag, assuming a galactic dust-to-gas ratio (Güver & Özel 2009). The location of GRB 200522A within its host ($\sim 1.1$ kpc from the centre) and evidence for ongoing star formation ($\sim 2-6 M_\odot \text{ yr}^{-1}$) also support that dust effects might not be completely negligible, as instead assumed by Fong et al. (2020).

We constrain the afterglow parameters to: $E_j \approx 6 \times 10^{48} \text{erg}$, $n_0 \approx 2 \times 10^{-3} \text{ cm}^{-3}$, $p \approx 2.3$, and identify the presence of a jet-break at $\lesssim 5$ d. From this we derive an opening angle of $\theta_j \approx 0.16 \text{ rad}$ ($9^\circ$), providing additional evidence that short GRB outflows are collimated into jets with a narrow core (e.g. Burrows et al. 2006; Troja et al. 2016). Since this GRB was likely observed close to its jet-axis ($\theta_j, \theta_c \lesssim 2$; for comparison, GW170817 had $\theta_j, \theta_c \approx 6$; Beniamini, Granot & Gill 2020; Ryan et al. 2020), no significant constraint can be placed on the jet structure and a simple top-hat jet profile seen on-axis ($\theta_j \approx 0$) already provides an adequate description. Our best-fitting model cannot reproduce the early radio detection with a simple FS emission, suggesting the presence of an early RS component (see also Jacovich et al. 2020, for a discussion of SSC effects).

A different interpretation is of course that the red colour of the optical/NIR emission marks the onset of a luminous kilonova. Statistically, this scenario (models FS + BB and FS + BB + Ext in Table 5) is not preferred over a simple afterglow model (FS + Ext in Table 5) and therefore a kilonova component is not required by the data. Nevertheless, we explore the range of kilonova models consistent with our data set. A radioactively powered kilonova with wind ejecta mass $M_{\text{ej},w} = 0.1 M_\odot$, wind velocity $v_{\text{ej},w} = 0.15 c$, and dynamical ejecta velocity $v_{\text{ej},d} = 0.3 c$ is capable of reproducing the observed NIR emission when considering a toroidal morphology for the lanthanide-rich ejecta (Korobkin et al. 2020). This geometry can naturally produce brighter transients than spherically symmetric counterparts of equal mass, expansion velocity, and radioactive heating. The range of dynamical ejecta masses is, however, not well constrained, as the rest-frame wavelengths probed by the observations lie in the optical band.

The ejecta mass implied by the NIR luminosity is slightly larger than the values derived for AT2017gfo ($M_{\text{ej},w} \approx 0.02-0.07 M_\odot$), and pushes the boundaries of a standard NS merger model. Numerical simulations of accretion discs indicate that, following an NS merger, $\approx 10-40$ per cent of the disc can become unbound and form a massive outflow along the polar axis (see e.g. Perego, Radice & Bernuzzi 2017). Since these mergers can form discs up to $\approx 0.3 M_\odot$, a wind ejecta mass $M_{\text{ej},w} = 0.1 M_\odot$ is still within the range of possible outcomes (e.g. Giacomazzo et al. 2013; Radice et al. 2018c; Kiuchi et al. 2019; Fernández, Foucart & Lippuner 2020; Fujibayashi et al. 2020). Such a large amount of wind ejecta can be expected for a progenitor system comprising either low-mass NSs (for an NS–
NS binary) or an NS–BH system where the BH has a favourable combination of high spin, $\chi > 0.5$, and low mass, $M_{\text{BH}} < 5M_\odot$ (e.g. Giacomazzo et al. 2013; Fernández et al. 2020).

Moreover, our derived ejecta mass is limited by the resolution of the LANL simulations that do not fully probe the range 0.03–0.1 $M_\odot$. It is conceivable that a finer sampled grid of simulated light curves could find additional solutions in this mass range. Based on these considerations, we find no compelling evidence for a magnetar-powered kilonova discussed by Fong et al. (2020).

Our study of GRB 160624A and GRB 200522A demonstrates that deep HST observations can probe an interesting range of kilonova behaviors out to $z \sim 0.5$. However, whereas sensitive HST imaging can detect the bright kilonova emission, it is not sufficient to unambiguously identify a kilonova and disentangle it from the standard afterglow. Observations of GRB 200522A, based on a single multicolour epoch, cannot break the degeneracy between the different models and, overall, the presence of a kilonova cannot be confidently established. As shown by previous cases, such as GRB 130603B and GRB 160821B, multietoch multicolour observations are essential for the identification of a kilonova bump. Moreover, at these distances, we found that the component of lanthanide-rich ejecta is only weakly constrained by the HST observations, with an allowed range of masses that spans two orders of magnitude (0.001–0.1 $M_\odot$). Future IR observations with JWST will be pivotal to constrain the properties of lanthanide-rich outflows from compact binary mergers.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request for research purposes to the corresponding author.

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