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Short GRB 160821B: A Reverse Shock, a Refreshed Shock, and a Well-sampled Kilonova


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Abstract

We report our identification of the optical afterglow and host galaxy of the short-duration gamma-ray burst sGRB 160821B. The spectroscopic redshift of the host is $z = 0.162$, making it one of the lowest redshift short-duration gamma-ray bursts (sGRBs) identified by Swift. Our intensive follow-up campaign using a range of ground-based facilities as well as Hubble Space Telescope, XMM-Newton, and Swift, shows evidence for a late-time excess of optical and near-infrared emission in addition to a complex afterglow. The afterglow light curve at X-ray frequencies reveals a narrow jet, that is refreshed at $>1$ day post-burst by a slower outflow with significantly more energy than the initial outflow that produced the main GRB. Observations of the 5 GHz radio afterglow shows a reverse shock into a mildly magnetized shell. The optical and near-infrared excess is from their putative host galaxies (e.g., Fong et al. 2013; Tunnillie et al. 2014). A kilonova is consistent with a binary neutron star merger resulting in a short-lived massive neutron star. This optical and near-infrared data set provides the best-sampled kilonova light curve without a gravitational wave trigger to date.

Key words: gamma-ray burst; individual (GRB 160821B) – stars: neutron

1. Introduction

Short-duration gamma-ray bursts (sGRBs) are widely thought to result from the merger of a binary neutron star (BNS) or a neutron star and a stellar mass black hole system. A fraction of the neutron star matter disrupted during the inspiral or collision will undergo rapid accretion onto the remnant object and launch an ultra-relativistic jet (e.g., Nakar 2007; Gehrels et al. 2009). Energy dissipation within such a jet produces a GRB, and, as this outflow decelerates, an external shock forms producing broadband afterglow emission. This progenitor model is supported by the fact that well-localized sGRBs (mainly the sample discovered by the Neil Gehrels Swift Observatory, hereafter referred to as Swift) appear to be produced in a wide range of stellar populations, including those with no recent star formation, and on occasions at large distances (tens of kiloparsecs in projection) from their putative host galaxies (e.g., Fong et al. 2013; Tunnillie et al. 2014). A further signature of compact binary mergers involving neutron stars is via the observation of a slower transient, variously called a “macronova” (Kulkarni 2005), “kilonova” (Metzger et al. 2010), or “merger-nova” (Gao et al. 2015; in this paper we shall use the term kilonova). A kilonova is powered by the radioactive decay of heavy, unstable, neutron-rich species created from decompressed neutron star material, which is ejected during the merger (e.g., Li & Paczynski 1998). The first compelling observational evidence for such a kilonova was the case of sGRB 130603B, for which excess near-infrared emission was detected in Hubble Space Telescope (HST) imaging at about one week in the rest frame after the
event (Berger et al. 2013; Tanvir et al. 2013). That this excess appeared in the near-IR tallied with predictions that the same heavy r-process elements created in the kilonova should produce dense line-blanketing in the optical, leading to emission appearing in the near-IR in the days to weeks following the merger (Barnes & Kasen 2013; Kasen et al. 2013; Tanaka & Hotokezaka 2013). Further interest in these events comes from the fact that this process of radioactive decay naturally leads to stable r-process elements, thus potentially explaining the abundances of more than half the elements in the universe heavier than iron (e.g., Lattimer & Schramm 1974; Freiburghaus et al. 1999; Rosswog et al. 2018). Mapping the diversity and evolution of kilonova events over cosmic time is therefore an essential ingredient to quantifying their global contribution to nucleosynthesis.

At a redshift of $z = 0.36$ (de Ugarte Postigo et al. 2014), identifying the kilonova emission in the afterglow to sGRBs 130603B was challenging and would not currently be feasible at higher redshifts, where the bulk of well-localized sGRBs have been found. Indeed, state-of-the-art modeling of neutron star binary mergers suggests that ejection of sufficient material to create a kilonova as bright as this is unlikely to happen in most mergers, and may require special circumstances such as a high mass ratio for the components of the binary (e.g., Hotokezaka et al. 2013; Just et al. 2015; Sekiguchi et al. 2016). Nonetheless, following this discovery, and based on archival data, possible kilonova signatures were identified via a late-time $I$-band excess emission in two earlier GRBs; namely, sGRB 050709 at $z = 0.16$ (Jin et al. 2016) and GRB 060614 at $z = 0.125$ (Yang et al. 2015). More recently, it has been proposed that the optical counterparts identified for sGRB 070809 at $z = 0.22$ (Jin et al. 2019, although note that the host identification, and therefore redshift, in this case is rather uncertain) and sGRB 150101B at $z = 0.13$ (Troja et al. 2018) may have been dominated by kilonova emission. For GRB 060614 the claim is particularly controversial in that its prompt duration, $T_{90} \sim 100$ s, is much longer than the canonical $T_{90} < 2$ s for a sGRB. However, the absence of an accompanying bright supernova combined with it exhibiting an initial spike of gamma-rays with durations of only a few seconds has led to speculation that it could have been produced by a compact binary merger (Gal-Yam et al. 2006; Gehrels et al. 2006; Perley et al. 2009; Kann et al. 2011).

The recent multimessenger observation of the BNS merger GW170817, discovered via gravitational waves and associated with a burst of $\gamma$-rays, GRB 170817A, detected by Fermi and INTEGRAL (Abbott et al. 2017a, 2017b; Goldstein et al. 2017; Savchenko et al. 2017), provided an opportunity to test directly the merger progenitor model. GRB 170817A appeared faint when compared to the cosmological sample of sGRBs and by considering the compactness problem and lack of an early afterglow indicates that the burst of $\gamma$-rays is unlikely to be a typical sGRB seen off-axis (e.g., Lamb & Kobayashi 2018; Ziaeepour 2018; Matsumoto et al. 2019); however, Ioka & Nakamura (2019) show that the observed GRB emission likely originates from a “mid”-region of a structured outflow. The rapid decline and superluminal motion of the late-time afterglow to GW170817 offer strong support for the sGRB–BNS association (Mooley et al. 2018; van Eerten et al. 2018; Ghirlanda et al. 2019; Lamb et al. 2019). Additionally, a kilonova was seen to follow GW170817, and monitored intensively at UV, optical, and near-infrared wavelengths (e.g., Andreoni et al. 2017; Coulter et al. 2017; Cowperthwaite et al. 2017; Drout et al. 2017; Evans et al. 2017; Kasliwal et al. 2017b; Pian et al. 2017; Smartt et al. 2017; Tanvir et al. 2017; Utsumi et al. 2017). By scaling the well-sampled GW170817 kilonova light curve to the distance of sGRBs with afterglows, attempts have been made to investigate the diversity of the kilonova population (Ascenzi et al. 2019; Gompertz et al. 2018; Rossi et al. 2019).

Here we report a search with HST, XMM-Newton, and ground-based telescopes including the Gran Telescopio Canarias (GTC), the Nordic Optical Telescope (NOT), the Telescopio Nazionale Galileo (TNG), the William Herschel Telescope (WHT), and the Karl G. Jansky Very Large Array (VLA) for afterglow and kilonova emission accompanying sGRB 160821B, associated with a morphologically disturbed host galaxy at $z = 0.162$. We supplement these data with publicly available and/or published in other sources Swift, VLA, and Keck data. Throughout we assume a flat universe with $\Omega_m = 0.308$ and $H_0 = 67.8$ km s$^{-1}$ Mpc$^{-1}$ (Planck Collaboration et al. 2016). Optical and near-IR magnitudes are reported on the AB system. In Section 2 we report the observations at X-ray, optical, near-IR, and radio frequencies plus the identification of the afterglow and the host. The results, interpretation, and afterglow and kilonova modeling are shown in Section 3. We discuss these results in Section 4 and give concluding remarks in Section 5.

2. Observations

2.1. Discovery of sGRB 160821B

The Burst Alert Telescope (BAT) on board Swift triggered on sGRB 160821B on 2016 August 21 at 22:29 UT. The reported duration of the burst was $T_{90}(15–350$ keV) $= 0.48 \pm 0.07$ s (Palmer et al. 2016). The burst was also detected by Fermi/GBM, from which a somewhat longer duration of $\approx 1$ s was found (Stanbro & Meegan 2016). Lü et al. (2017) performed a joint fit to the Swift/BAT and Fermi/GBM data, finding the total fluence in the 8–10,000 keV band of $(2.52 \pm 0.19) \times 10^{-6}$ erg cm$^{-2}$. This corresponds to an isotropic energy, assuming the redshift of $z = 0.162$, of $E_{\gamma, \text{iso}} = (2.1 \pm 0.2) \times 10^{50}$ erg, fairly typical of the population of short GRBs with measured redshifts (Berger 2014).

2.2. Afterglow Identification

After slewing, the X-ray Telescope (XRT) on Swift detected a fading afterglow that provided a refined localization, and from the X-ray spectrum found no evidence for significant absorption beyond that expected due to foreground gas in our Galaxy (Sbarufatti et al. 2016). As described below, our early optical imaging identified the afterglow of the burst and a prominent nearby galaxy at a separation of about 5″” (Xu et al. 2016).

With a magnitude of $r \approx 19.4$ (Section 2.3), the probability of the chance alignment of an unrelated galaxy of this brightness or brighter this close to the line of sight is $P_{\text{chance}} \approx 1.5$% (using the formalism of Bloom et al. 2002, and although low, is not entirely negligible. However, the absence of any faint underlying quiescent emission in our final HST epochs (see Section 2.2), which might otherwise suggest a higher redshift host, adds support to our working hypothesis that this is the host galaxy of sGRB 160821B.
The NOT, located in the Canary Islands (Spain), began optical observations at 23:02 UT, only 33 minutes post-burst. These revealed an uncatalogued point source within the X-ray error region, presumed to be the optical afterglow (Xu et al. 2016). The best astrometry came from our HST images, and gave a position of R.A.(J2000) = 18:39:54.550, decl.(J2000) = +62:23:30.35 with an uncertainty of ±0.0003 in each coordinate, registered on the GAIA DR2 astrometric reference frame (Gaia Collaboration et al. 2016, 2018). Fong et al. (2016) reported a detection of the radio afterglow at 5 GHz with the VLA, which provided a burst location of R.A.(J2000) = 18:39:54.56, decl. (J2000) = +62:23:30.3 (reported error 0″3), consistent with our HST localization.

2.3. Host Galaxy and Redshift

The position of the proposed host galaxy measured from our HST images is R.A.(J2000) = 18:39:53.968, decl.(J2000) = +62:23:34.35. We obtained spectroscopy of this galaxy with the WHT using the Auxiliary Port Camera (ACAM), in observations beginning on 2016 August 22 at 22:57 UT (Levan et al. 2016). The data were reduced using standard IRAF routines. The resulting 2D and 1D extracted spectra are shown in Figure 1, with emission lines of Hα, Hβ, [S II], and [O III] providing a redshift of z = 0.1616 ± 0.0002. The slit was aligned to cross both the nucleus of the main galaxy and a fainter blob of emission to the north, labeled “B” and “C,” respectively, on Figure 2. The latter turned out to be a higher redshift galaxy23 at z = 0.4985 ± 0.0002, the spectrum of which is also shown in Figure 1.

At a redshift z = 0.162 the separation between afterglow and host corresponds to 16.4 kpc in projection, which is consistent with the offset distribution found for other sGRBs (Fong & Berger 2013; Tunnicliffe et al. 2014).

Morphologically, the host appears to be a face-on, disturbed spiral galaxy (Figure 2). The extended, warped appearance of the central bulge suggests an ongoing merger, and the nebular emission lines are consistent with active star formation. It is interesting to note, although most likely coincidental, that the hosts of both sGRB 130603B and GRB 170817A were also notably disturbed (Tanvir et al. 2013; Levan et al. 2017).

The foreground extinction corrected magnitude of the host from the HST imaging (with the flux from the z = 0.5 background galaxy subtracted) is re060.0 = 19.4. This corresponds to an absolute magnitude of Mr = −20.0, which is ≈L∗/3 with respect to the Loveday et al. (2015) “blue” (star-forming) galaxy population.

The r-band 25 mag arcsec−2 isophote has a radius of ≈3″5, corresponding to a linear scale of ≈10 kpc. However, it is possible to trace lower surface brightness emission from the galaxy out to the GRB location, albeit at a faint surface brightness level of ≈27 r mag arcsec−2.

2.4. Further Optical and Near-infrared Monitoring

sGRB 160821B is among the lowest redshift sGRBs found by Swift to date. This, combined with its comparatively low foreground Galactic extinction of A_V = 0.118 mag (Schlafly & Finkbeiner 2011), motivated an intensive follow-up monitoring campaign.

Further optical and near-IR imaging was obtained with the NOT, the GTC, and the WHT over the next several nights. These data were reduced using standard procedures, and

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23 For completeness, we note that the impact parameter of the GRB from this background galaxy is ≈50 kpc, and it has a P_{chance} ≈ 40%, confirming that it is not a good alternative host candidate.
calibrated photometrically using Pan-STARRS (optical) and 2MASS (near-IR) stars in the field.

Observations with the HST using the Wide Field Camera 3 (WFC3), were obtained in the F606W filter (a wide filter spanning approximately the V and r bands), the F110W filter (a wide YJ band), and the F160W filter (H band) from several days to several weeks post-burst (Troja et al. 2016). We adopted the standard photometric calibration for these bands, and aperture corrections were determined using bright point sources on the frames.

In all cases, interactive aperture photometry was performed using the Gaia software. Care was taken to obtain sky estimates close to the position of the transient, because the background was not entirely free of light from the host galaxy.

These observations revealed the counterpart to be initially steady in brightness during the observations made on the first night, but thereafter it faded monotonically in all bands. In the third HST visit, at ~23 days, no emission is detected at the burst location, which was confirmed by a final visit at ~100 days. A summary of the results of all our optical and near-IR photometry for the sGRB 160821B afterglow, together with selected magnitudes reported elsewhere, is presented in Table 1.

Table 1

<table>
<thead>
<tr>
<th>Δt (day)</th>
<th>t_exp (s)</th>
<th>Telescope/Camera</th>
<th>Filter</th>
<th>A_B</th>
<th>Source of Photometry</th>
</tr>
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<tr>
<td>0.95</td>
<td>14 × 300</td>
<td>TNG/DOLoRes</td>
<td>g</td>
<td>24.02 ± 0.16</td>
<td>This work</td>
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<tr>
<td>2.02</td>
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<td>GTC/OSIRIS</td>
<td>g</td>
<td>25.56 ± 0.16</td>
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<td>3.98</td>
<td>10 × 120</td>
<td>GTC/OSIRIS</td>
<td>g</td>
<td>25.98 ± 0.15</td>
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<tr>
<td>6.98</td>
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<td>GTC/OSIRIS</td>
<td>g</td>
<td>26.90 ± 0.18</td>
<td>This work</td>
</tr>
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<td>6 × 300</td>
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<td>r</td>
<td>22.58 ± 0.09</td>
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<td>r</td>
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<td>r</td>
<td>22.53 ± 0.03</td>
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<td>1.06</td>
<td>6 × 240</td>
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<td>r</td>
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<td>r</td>
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<td>i</td>
<td>22.37 ± 0.03</td>
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<td>z</td>
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<td>z</td>
<td>23.90 ± 0.23</td>
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</tr>
<tr>
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<td>9 × 300</td>
<td>NOT/AIROS</td>
<td>z</td>
<td>24.34 ± 0.24</td>
<td>This work</td>
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<tr>
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<td>GTC/OSIRIS</td>
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<td>2397</td>
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<td>0.96</td>
<td>33 × 20</td>
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<td>H</td>
<td>23.83 ± 0.35</td>
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<td>F160W</td>
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<tr>
<td>23.23</td>
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<tr>
<td>4.3</td>
<td>45 × 30.8</td>
<td>Keck/MOSFIRE</td>
<td>K</td>
<td>24.04±0.04</td>
<td>Kasliwal et al. (2017a)</td>
</tr>
</tbody>
</table>

Note. Column (1): midtime of observation with respect to GRB trigger time. Magnitudes corrected for Galactic foreground extinction according to A_V = 0.118 from Schlafly & Finkbeiner (2011).

2.5. X-Ray Monitoring

Swift/XRT monitoring continued for 2.5 days, showing evidence for a significant break to a steeper rate of fading around 0.4 days. Our XMM-Newton observations comprised two visits at approximately 4 and 10 days post-burst. The first visit produced a very significant detection, and was above a simple extrapolation between the last Swift visits. This is discussed further in Section 3.

A summary of the X-ray observations is presented in Table 2.

2.6. Radio Monitoring

The 5 GHz radio detection in 1 hr of observations at 3.6 hr after the burst had a reported flux density of ~35 μJy; an additional observation with the same telescope at 26.5 hr post-burst returned a 3σ upper limit of 18 μJy (Fong et al. 2016).

Late-time radio observations of the GRB 160821B field were carried out with the VLA, at a central frequency of about 10 GHz and nominal bandwidth of 4 GHz. The first observation started on 2016 September 1 at 23:24:16 UT; the second observation started on 2016 September 8 at 00:10:33 UT. Data were calibrated using the automated VLA calibration pipeline available in the Common Astronomy Software Applications (CASA). After calibration, data were inspected for flagging, and then imaged using the CLEAN algorithm available in

http://www.stsci.edu/hst/wfc3/phot_zp_lbn

http://astro.dur.ac.uk/~pdrapear/gaia/gaia.html
Table 2

<table>
<thead>
<tr>
<th>Column</th>
<th>0.3–10 keV Flux (10^{-14} erg cm^{-2} s^{-1})</th>
</tr>
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<td>t (day)</td>
<td></td>
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<tr>
<td>0.06±0.01</td>
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<td>1.02±0.09</td>
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<td>1.70±0.21</td>
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<tr>
<td>9.95±0.17</td>
<td>0.51±0.20</td>
</tr>
</tbody>
</table>


### 3. Light-curve Behavior, Interpretation, and Modeling

In this section we describe the behavior of the light curve at various observed frequencies. Additionally, we give our interpretation of this behavior before estimating the light curve with physically motivated models. These models provide parameter estimates for the various contributing emission components.

#### 3.1. X-Ray Frequency Light-curve Behavior

A period of extended emission\(^{25}\) (EE) follows the sGRB 160821B prompt emission for a duration of \(\sim 200–300\) s. Following the rapid decline of the EE, Swift/XRT, and XMM-Newton observations show a shallower decline between \(\sim 0.01\) and 10 days; as expected from an afterglow. However, this late-time X-ray flux deviates from the expected power-law decline of a simple afterglow model. The flux level drops below that expected from a power-law decay between \(\sim 0.3\) and 4 days. Rebinning the Swift/XRT data into photon bins with a lower minimum count, the behavior of the X-ray light curve is more clearly revealed; see Figure 3 where the gray markers show the data using the typical minimum photon count per bin and the black markers show the rebinned flux levels (a triangle indicates an upper limit). A photon index \(\Gamma = 1.7\) is assumed, which is consistent with both Swift/XRT (\(\Gamma = 2.0^{+0.7}_{-0.4}\)) and XMM-Newton (\(\Gamma = 1.4^{+0.5}_{-0.2}\)). Horizontal error bars indicate the duration of the observations at each point. The rebinned data reveal a break in the X-ray light curve at \(\sim 0.35\) days, where the flux drops significantly for all the following data, and the flux level at \(2–3\) days is comparable to the XMM-Newton observed flux level at \(\sim 4\) days.

#### 3.2. Behavior at Optical and Near-infrared Frequencies

Figure 4 shows the spectral energy distribution of all the optical data from Table 1, where we have averaged together
points taken in the same filter at close to the same time. The color evolution of the transient exhibits a trend from blue in observations taken roughly one day after the burst to a much redder color in all subsequent detections. This is immediately evident; the behavior at optical and near-IR is distinct from the behavior at X-ray frequencies (see Section 3.1). The deviation from a power law with an excess in blue and then red is evident; the behavior at optical and near-IR is distinct from that at 1 keV.

We note that while treating the F606W magnitudes as r-band in principle introduces a systematic error, the measured g-F606W color is flat (consistent with our interpretation below that the optical light is afterglow dominated at these times), indicating that color corrections would be smaller than the photometric errors. (Furthermore, even for our kilonova models, at the time of those epochs, the predicted difference between F606W and the r-band is \( \lesssim 0.2\) AB mag.)

3.3. At Radio Wavelengths

Radio observations show a fading source between \( \sim 0.1\) and 1 day, but a detection at \( \sim 10\) days indicates continued radio afterglow emission as shown by the red contours in Figure 2 (note that the small apparent offset between the radio and optical positions is consistent with the effects of noise in the radio map, given the low S/N). The late afterglow is limited by a nondetection at \( \sim 17\) days.

3.4. Interpretation

A kilonova component is likely to peak in the optical within one to two days post-merger, leading us to expect the r-band flux to be dominated by afterglow at the early (\( \sim 0.1\) days) and late (\( \sim 10\) days) epochs. Inspection of the spectral energy distribution at \( \sim 0.1\) days between the X-ray (1 keV) and the r-band optical data reveals \( \beta = 0.66 \pm 0.03\), where \( F_\nu \propto \nu^{-\beta}\), and is consistent with \( \beta = 0.68 \pm 0.07\) at \( \sim 10\) days in agreement with this expectation (see Figure 3). Using the broader spectral index limits at \( \sim 10\) days, and assuming a temporal decline as \( F_\nu \propto t^{-\alpha}\), where \( \alpha = 3(p - 1)/4\), the power-law behavior for the limits on \( p \) from \( p = 2\beta + 1 \) is shown. A break in the light curve at \( t_1 \sim 7\) days is required, where \( \alpha = -p \) at \( t > t_1\); this break will be achromatic. The X-ray light curve drops significantly below the lower limit (\( p = 2.23\) power-law extrapolated to earlier times from \( \sim 4\) days.

The X-ray light curve exhibits an earlier break at \( t \sim 0.35\) days, and a late-time excess. Afterglow variability is discussed in Ioka et al. (2005), and such an excess is expected from either a refreshed shock where a slower shell catches up with the initial decelerating outflow (e.g., Panaitescu et al. 1998; Zhang & Mészáros 2002), or a structured jet with an angle-dependent energy and Lorentz factor distribution (e.g., Lamb & Kobayashi 2017). By assuming the jet structures used to model the afterglow to GRB 170817A in Lamb et al. (2019), where on axis the resultant GRB would have been consistent with the short GRB population (e.g., Salafia et al. 2019), then from the observed \( \gamma\)-ray energy of GRB 160821B we can estimate the system inclination following Ioka & Nakamura (2019). For a Gaussian structure with GRB 170817A-like core energy [\( \log_{10}(E_\gamma) = 52.4^{+0.4}_{-0.3}\)], then to reproduce the prompt \( \gamma\)-ray energy of GRB 160821B, the system should be inclined at \( \sim \theta_{\text{c}} + (3 \pm 2)\) (see also Troja et al. 2019); for a two-component jet [\( \log_{10}(E_\gamma) = 52.0^{+1.0}_{-0.9}\)], then the opacity of the low-\( \Gamma\) second component must be considered (e.g., Lamb & Kobayashi 2016) and the expected inclination would be \( \sim \theta_{\text{c}} + 1.5 \pm 1.5\). For a structured jet, however, a late-time rebrightening in the afterglow is only expected for some structure profiles and at higher inclinations, \( \sim (3-5) \times \theta_{\text{c}}^{28}\) where bright \( \gamma\)-ray emission is not expected (see Lamb & Kobayashi 2017, 2018; Gill & Granot 2018; Beniamini & Nakar 2019; Matsumoto et al. 2019). Considering the bright GRB we assume that GRB 160821B is on axis or very close to on axis, where the resultant afterglow would behave similarly to the on-axis case regardless of the jet structure (see Lamb & Kobayashi 2017). For our working model we favor a refreshed shock scenario with two shells where the \( \Gamma_1 > \Gamma_2\), where the subscript indicates the shell order. If the jet breaks at \( t \sim 0.35\) days, then the apparent break at \( t > 4\) days is indicative of a turnover in the light curve following a significant energy injection episode.

The extended emission at X-ray frequencies lasting until \( \sim 200-300\) s post sGRB 160821B supports continued engine activity beyond the timescale of the GRB. This X-ray emission is consistent with an outflow episode driven by fallback accretion onto a spinning black hole (Rosswog 2007; Metzger et al. 2008; Nakamura et al. 2014; Kisaka & Ioka 2015; Yu et al. 2015; Kisaka et al. 2017). A peak or break time of \( \sim 4\) days for the refreshed shock indicates that the bulk Lorentz factor of the outflow when the second shell catches the first should be low, with \( \Gamma_1(t) \sim 10\) and the second shell will have a Lorentz factor much lower than the value typically expected for a successful GRB, \( \Gamma_2 \ll 100\). Energy dissipated within a low-\( \Gamma\) outflow is not expected to be emitted at \( \gamma\)-ray energies; \( \gamma\) rays injected into the outflow will be coupled to the plasma and these photons will adiabatically cool and thermalize due to scattering. The effect of these processes is to suppress any resulting emission, which will have a spectral peak at \( \sim X\)-ray frequencies. Photons that fail to escape from a low-\( \Gamma\) jet will be

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28 A late excess/rebrightening is not expected from a Gaussian profile structure.
reabsorbed by the outflow and contribute to the jet kinetic energy driving the afterglow (Kobayashi & Sari 2001; Kobayashi et al. 2002; Lamb & Kobayashi 2016). The energy-loss by the photon distribution and reabsorption by the outflow will result in a very low value for the emission efficiency, $\eta$. This low-$\Gamma$ X-ray extended emission producing shell follows the initial, high-$\Gamma$, GRB producing shell, which will decelerate as $\Gamma_G(t) \propto t^{-3/8}$ as it sweeps-up the ambient medium. However, the second shell encounters very little material and will catch up with the forward shell when $\Gamma_G(t) \approx \Gamma_{G,2}/2$ (Kumar & Piran 2000). The energy of the second shell refreshes the forward shock resulting in a rebrightening of the afterglow (e.g., Granot et al. 2003).

Although limited, the observations at radio frequencies place tight constraints on any possible afterglow, and the afterglow parameters will be constrained by the detection and upper limits at 1–10 days. The early radio detection at $\sim$0.1 days, brighter than the previous upper limits and flux at $\sim$10 days, is likely the result of a reverse shock (e.g., Mészáros & Rees 1997; Sari & Piran 1999; Kobayashi 2000; Kobayashi & Sari 2001; Resmi & Zhang 2016; Lamb & Kobayashi 2019). Given the X-ray to optical spectral index $\beta \sim 0.66$, the 5 GHz radio emission at $\sim$0.1 days is below the characteristic synchrotron frequency $\nu_m^\star$ if the $\sim$0.1 day radio emission at 5 GHz belongs to the forward shock, then as $F_\nu \propto \nu^\beta$, and considering the flux at X-ray frequencies $F_\nu = F_\nu,\text{max}(\nu_\gamma/\nu_m)\beta/3$ and the critical frequency $\nu_m^\star \propto n^{-1/2} \theta_j^{-3/2}$ Hz giving $\nu_m \sim 10^{22} \text{ Hz}$. As $\nu_m \propto \Gamma_{G,2}^{-3/2}$ and $\Gamma_{G,2}$ for the afterglow before and after the jet break, the 5 GHz radio emission will brighten until a peak when $\nu_m \sim 500 \text{ GHz}$ or the jet breaks; in either case, the upper limit of 18 mJy at $\sim$1 day post sGRB 160821B rules out the earlier detection being due to the forward shock. This is the first successfully modeled candidate of a reverse shock in an unambiguous sGRB afterglow and indicates that, in some cases, emission from the reverse shock can be bright despite previous nondetections (Lloyd-Ronning 2018; however, see Becerra et al. 2019 where a reverse shock was recently claimed for the candidate short GRB 180418A). Any afterglow model that can explain the behavior at X-ray frequencies and the early and late optical and near-IR should also be consistent with the detection and limits at radio frequencies.

The afterglow at both radio and X-ray frequencies can constrain the behavior at optical and near-IR. These observations indicate an excess in blue at early times followed by a reddening; this behavior is indicative of a kilonova. Previous studies of sGRB 160821B have been restricted to much smaller photometric data sets and consequently have only drawn weak conclusions about the possibility of a kilonova component and the nature of the afterglow (Kasliwal et al. 2017a; Gompertz et al. 2018; Jin et al. 2018). Here, we use the X-ray, early optical and radio constraints on the afterglow emission to interpret the kilonova contribution at optical and near-IR frequencies. We use the latest kilonova light-curve models based on numerical-relativity simulations to constrain the dynamical and post-merger ejecta masses (e.g., Kawaguchi et al. 2018).

### 3.5. Afterglow Modeling

We use the analytic solution for a relativistic blast wave from Pe’er (2012), and the method for generating afterglow light curves from Lamb et al. (2018) to estimate the broadband afterglow for a given set of parameters. We use the observed data to constrain several of the GRB afterglow parameters. As the optical flux at $\sim$10 days could still have some kilonova contribution, we use the 1 keV to $\text{r}$-band spectral slope at $\sim$0.05 days to estimate $p$, where $\beta \sim 0.66$ giving $p = 2.3$. If we assume a prompt efficiency of $\eta \sim 0.1$–0.15 (Fong et al. 2015), then the isotropic equivalent kinetic energy in the initial outflow is $E_{k,iso} \sim (1–2) \times 10^{51} \text{ erg}$. Throughout, we fix $\epsilon_B = 0.01$ for the forward shock, consistent with the range for short GRBs (Fong et al. 2015).

The optical flux is approximately flat between 0.05 and 0.07 days; this flatness combined with a likely reverse shock in the radio at the same time indicates that these points coincide with the deceleration timescale for the outflow. By fixing the ambient density to $n = 10^{-4} \text{ cm}^{-3}$, consistent with the location in the outskirts of the host galaxy (see Figure 2), the Lorentz factor of the GRB outflow can be estimated; $\Gamma_0 \sim 18 [t_d/(1 + z)]^{-3/8} (E_{k,iso}/10^{51} \text{ erg})^{1/8} \left(\eta/10^{-4} \text{ cm}^{-3}\right)^{-1/8} \sim 55–60$, where $t_d \sim 0.06$ days is the deceleration time. Similarly, the break at $t_j \sim 0.35$ days can be used to estimate the jet half-opening angle, $\theta_j \sim 0.05 [t/(1+z)]^{3/8} (E_{k,iso}/10^{51} \text{ erg})^{-1/8} \left(\eta/10^{-4} \text{ cm}^{-3}\right)^{1/8} \sim 0.033$ rad, or $\sim 1.9'$. As the break time dominates the opening angle estimation, we can put weak limits on this value of $1.9_{-0.03}^{+0.03}$ degrees (these small errors are only the formal fit uncertainty given this choice of jet model and decomposition of the light curve; the systematic errors from uncertainties in the model assumptions are much greater, and poorly quantifiable), this narrow jet is consistent with the opening angle range for short GRBs (Jin et al. 2018).

The forward shock is refreshed at $\sim$1 day, peaking at $\sim$3 days and then declining as $\sim r^{-\beta}$. We assume that the second shell has the same half-opening angle as the first. As the jet has broken, sideways expansion could widen the initial blast wave and the second shell will only refresh the blast wave with an opening angle $\leq \theta_j$. By assuming that the radius of the blast wave is roughly constant after the jet break, then the Lorentz factor of the second shell is

$$\Gamma_{G,2} \gtrsim 47.4 \left(\frac{1+z}{t_c}\right)^{1/2} \left(\frac{E_{k,iso}}{10^{51} \text{ erg}}\right)^{1/6} \left[\frac{n}{10^{-4} \text{ cm}^{-3}}\right]^{-1/6} r_j^{3/4},$$

(1)

where $\Gamma_{G,2} \gtrsim 16$ for an observed collision time $t_c \sim 1$ day. The Lorentz factor of the forward shock at the collision is then $\Gamma_{G,1}(t) \gtrsim 8$.

We find that if the forward shock is refreshed when $\Gamma_{G,1}(t) = 12$ and the resulting blast wave has $12.5 \times E_{k,iso}$ of the initial outflow energy then the afterglow can account for the X-ray excess at $\sim$4 days. The radio afterglow at $\sim$10 days constrains the microphysical parameter $\epsilon_e \sim 0.3$, so as not to overproduce the radio flux. We assume throughout that the initial and final blast wave have identical microphysical parameters $\epsilon_B$ and $\epsilon_e$, electron index $p$, and $\theta_j$.

The early radio point at $\sim$0.1 days requires a significant reverse shock. For this point to be reverse shocked dominated the X-ray and optical data constrain the characteristic synchrotron frequency to $\nu_m \sim 10^{14} \text{ Hz}$, much lower than the model estimate of $\nu_m \sim 3.5 \times 10^{14} \text{ Hz}$. As $\nu_m \propto \Gamma_{G,2}^{4/3} n^{1/2} \beta_p^{1/6}$, then the parameters that can successfully explain the X-ray and

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29 The sideways expansion does not halt the radial progress of the jet (Granot & Piran 2012; Lamb et al. 2018); by assuming that it does, we can place a lower limit on the Lorentz factor of the second shell.
optical afterglow would need significantly lower values. Such lowered parameter values result in an afterglow that is inconsistent with the other observations and unphysical parameters in many cases. Following Harrison & Kobayashi (2013), the characteristic synchrotron frequency \( \nu_m \) and the maximum flux \( F_{\nu,\text{max}} \) for the reverse shock can be found from the forward shock parameters. The reverse shock flux before and after the peak will scale following Kobayashi (2000); for the thin shell case and our parameters, the flux pre-peak will scale as \( F_{\nu} \propto t^{-3.7} \) and post peak \( F_{\nu} \propto t^{-2.05} \). To accommodate the early radio detection, we need to use a magnetization parameter of \( R_B \sim 8 \). The model light curve is shown in Figure 5, where we have taken an initial kinetic energy of \( E_{\text{Kiso}} = 1.3 \times 10^{51} \text{erg} \) and \( \theta_j = 0.033 \), with all other parameters as discussed.

### 3.6. The Kilonova Modeling

The kilonova appears as an excess in the optical above the afterglow. From Figure 5, where the optical afterglow is shown as dotted lines, it is clear that all bands are in excess at \( \sim 1 \text{ day} \) post-burst. The bluer bands (\( g, r, \) and \( i \)) follow the afterglow from \( \sim 5 \text{ days} \) while the redder bands (\( J, H, \) and \( K \)) remain in excess until \( \sim 10 \text{ days} \) post GRB.

Using two-component kilonova models from Kawaguchi et al. (2018), \( K \)-corrected to \( z = 0.16 \), we find the model parameters via a \( \chi^2 \) minimization fit for the data to the kilonova plus model afterglow. The kilonova is best described\(^{30}\) by a secular ejecta (or post-merger wind driven by viscous and neutrino heating) with a mass \( M_{\text{pm}} = 0.01 \, M_\odot \), and a dynamic ejecta mass \( M_{\text{dyn}} = 0.001 \, M_\odot \). The density profile for each ejecta component is given by

\[
\rho(r, t) \propto \begin{cases} 
    \frac{r_0}{r^3} & 0.025c \leq r/t \leq 0.15c \\
    \frac{r_0}{r^6} \zeta(\theta) t^{-3} & 0.15c \leq r/t \leq 0.9c
\end{cases}
\]

(2)

where the top condition is for the secular ejecta, and the bottom condition for the dynamic ejecta. We find good fits for an upper limit for the secular ejecta velocity, and lower limits for the dynamic ejecta velocity, of \( 0.1-0.15c \). The function \( \zeta(\theta) \) describes the angular distribution of the dynamic ejecta, and is given by

\[
\zeta(\theta) = 0.01 + \frac{0.99}{1 + e^{20(\theta - \pi/4)}}
\]

(3)

where \( \theta \) is the angle from the central axis.

The element abundances for the ejecta are determined following the results of r-process nucleosynthesis calculations by Wanajo et al. (2014) and assuming that the secular and dynamic ejecta have initially flat electron fraction \( Y_e \) distributions ranging from 0.3 to 0.4 and from 0.1 to 0.4, respectively. Radiative transfer simulations were performed from 0.1 to 30 days resulting in a light curve with a statistical error in each band \( \sim 0.1-0.2 \text{ mag} \).

The kilonova fit to the data depends on the afterglow subtraction, however, the precise details of the afterglow parameters are not crucial. As the optical afterglow is typically in the same spectral regime as the observed X-ray data for sGRBs, and supported by the similar spectral index between optical and X-rays at 0.1 and 10 days, then the optical afterglow will follow that at X-ray frequencies during the kilonova peak. The X-ray data extrapolated to the optical at \( \sim 1-4 \text{ days} \)...
post-burst indicates that the afterglow contributes ~10%. The typical photometric uncertainty is ~10%, and the kilonova model uncertainty is ~10%. Combining these uncertainties, and using the analytic scaling for luminosity with mass \( L \propto M^2 \) (e.g., Grossman et al. 2014), we can give limits on the mass estimates from the kilonova model fit of ~±60%; however, we emphasize that both the masses and the uncertainties are model specific.

4. Discussion

We have shown that the afterglow of sGRB 160821B with extended X-ray emission until ~300 s post-burst exhibits a reverse shock at early times and a refreshed shock at late times. Early time observations at radio wavelengths require a reverse shock, while the complex light curve at X-ray frequencies observed by Swift/XRT and XMM-Newton, combined with late-time radio observations reveal a break at ~0.35 days and a rebrightening at >1 day. The jet is very narrow, at \( \theta_j \sim 1.9^\circ \), and the slower second outflow episode that refreshes the forward shock carries significantly more energy than the initial outflow. However, the total combined energy of the jets, \( E_j \sim 0.9 \times 10^{54} \) erg, is consistent with the short GRB population (Fong et al. 2015).

Extended emission can be the result of a magnetar (e.g., Fan & Xu 2006; Metzger et al. 2008; Bucciantini et al. 2012; Gompertz et al. 2013; Gibson et al. 2017), or energy dissipated within a jet launched due to mass fallback onto the central compact object (Fan et al. 2005; Rosswog 2007; Kisaka & Ioka 2015; Kisaka et al. 2017); see also Barkov & Pozanenko (2011) for a two-component jet model. The refreshed shock at late times requires a second episode of jet activity and fallback accretion onto the central compact object supports both this late-time rebrightening and the extended emission. From the afterglow modeling, the second jet episode has a Lorentz factor of \( \Gamma_2 \sim 24 \). Internal energy dissipation within such a low-\( \Gamma \) jet is expected to be suppressed due to a large optical depth, see Lamb & Kobayashi (2016); however, any resulting emission will peak at X-ray frequencies and have a longer timescale than the initial dissipation timescale. Considering the energy required to refresh the forward shock, the efficiency of energy dissipation within the fallback launched jet is \( \eta \sim 10^{-7} \), consistent with the expectation from a low-\( \Gamma \) outflow (Lamb & Kobayashi 2016). The fallback mass required to launch such an energetic second outflow can be estimated following Kisaka et al. (2017) giving a mass \( \sim 2 \times 10^{-3} M_\odot \).

As well as the EE and the refreshed shock, the afterglow reveals a reverse shock (the first confirmed reverse shock in an sGRB, see Lloyd-Ronning (2018), who highlight the lack of observed reverse shocks in sGRBs); such a shock propagates into the colder and denser inner shell. To recreate the reverse shock emission, we follow Lamb & Kobayashi (2019) and require a magnetization parameter of \( R_B \sim 8 \). Thus the magnetic field within the shell is much larger than the magnetic field induced by the forward shock. A high magnetic field indicates that the shell is endowed with primordial magnetic fields from the central engine.

In addition to these afterglow features, a kilonova is present at optical and near-IR frequencies. The best fitting model is one represented by a dynamic ejecta mass of \( \sim 0.001 M_\odot \) and a secular ejecta mass \( \sim 0.01 M_\odot \). The secular ejecta mass, required for the early blue excess, is consistent with the expectation of the mass-loss from a torus surrounding a massive neutron star (Fujibayashi et al. 2018; Fernández et al. 2019). However, the best-fit model from our parameter sample under-predicts the observed g-band emission at ~2 and ~4 days post-burst, this is likely due to the finite parameter spacing of the kilonova model samples. A small secular ejecta mass \( \sim 0.001 M_\odot \) and the low dynamic ejecta mass \( \sim 0.001 M_\odot \), may indicate that the remnant collapses to a black hole promptly after the merger (Kiuchi et al. 2009; Sekiguchi et al. 2016; Coughlin et al. 2018; Radice et al. 2018). In such a scenario the electron fraction, \( Y_e \), will be lower. To test this, we compared the kilonova light curve of the best-fit model with a model using a lower electron fraction distribution for the post-merger wind \( Y_e = 0.1-0.3 \) as expected from a prompt collapse scenario. A comparison of the light curves for these two scenarios was performed, the results indicate that the prompt collapse to a black hole, with a low-\( Y_e \) and a higher velocity, will overproduce the red excess at late times and underproduce the early blue excess; see Figure 6. Thus, the observed blue emission in the early phase suggests the existence of a low opacity component, when interpreted as kilonova emission, and we can conclude that a very prompt collapse to a black hole is unlikely to explain the observed transient when considering the observed features. Note that the afterglow subtracted data at \( \geq 4 \) days is typically brighter than the kilonova model we use, especially at \( K- \), \( J- \), \( r- \), and \( g- \) bands. This excess at bluer wavelengths is due to the afterglow subtraction, where the emission is afterglow dominated and the model afterglow slightly underpredicting the observed flux. The observed \( K- \) and \( J- \) band excesses (~4 and ~10 days post-burst) have large associated errors, and the best-fit model is within 2\( \sigma \) of each detection without considering the model uncertainty (see Figure 5).

Of the five widely discussed GRBs with candidate kilonova contributions to their light curvess—GRBs 050709, 060614, 070809, 130603B, and 150101B (Yang et al. 2015; Jin et al. 2016, 2019; Gompertz et al. 2018; Troja et al. 2018)—the kilonova in sGRB 160821B is the best sample. At \( \sim 0.011 M_\odot \), the kilonova in sGRB 160821B has an ejecta mass toward the lower end of the range proposed for any of these other cases, and is consistent with the \( < 0.03 M_\odot \) found by Kasliwal et al. (2017a). The kilonova following GW170817 had an ejecta mass \( \sim 0.03 - 0.05 M_\odot \) (e.g., Pian et al. 2017; Smartt et al. 2017), similar to the mass estimates for sGRB 130603B, \( \sim 0.03 M_\odot \) (e.g., Jin et al. 2016), whereas, GRB 050709, 060614, 070809, and 150101B have masses \( \sim 0.05, 0.13, 0.015, \) and \( < 0.004 M_\odot \), respectively (Yang et al. 2015; Jin et al. 2016). However, we note that upper limits implied by kilonova nondetection in some other sGRBs could indicate the existence of fainter kilonovae indicating still lower ejecta masses\(^{31}\) (e.g., Gompertz et al. 2018).

The best-fit kilonova model is consistent with the scenario where, following the merger, a massive neutron star survives for a short period (Fujibayashi et al. 2018). This scenario is similar to the case of GRB 170817A, for which various arguments point to a short-lived massive neutron star (e.g.,

\(^{31}\) The heating rates and therefore the estimated masses depend on the chosen nuclear mass formula (e.g., Barnes et al. 2016; Rosswog et al. 2017). For the very low \( Y_e \) ejecta the r-process path passes close to the neutron-drip line in the nuclear chart, this is experimentally uncharted territory, and we rely on purely theoretical mass formulae. The amounts of trans-lead nuclei, important because they are efficient in releasing energy and their decay products are efficiently thermalizing with the ambient medium, depend quite sensitively on the chosen mass formula.
secular ejecta, and the electron fraction supports the existence of a short-lived massive neutron star that does not immediately collapse to a black hole.

We have also presented *Swift* and *XMM-Newton* observations of the event and combining with constraints from VLA radio observations find a complex afterglow with a radio-emitting reverse shock into a magnetized shell and a late-time, broadband, refreshed shock. The jet is very narrow with \( \theta_j \sim 1^\circ \), and the second episode is significantly more energetic than the first. We find the prompt and extended emission, plus the early- and late-time rebrightening afterglow to be consistent with multiple accretion episodes onto the central compact object with the second episode consistent with a fallback mass of \( \sim 0.002 M_\odot \).

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