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The luminous, slow-rising orphan afterglow AT2019pim as a candidate moderately relativistic outflow

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ABSTRACT

Classical gamma-ray bursts (GRBs) have two distinct emission episodes: prompt emission from ultrarelativistic ejecta and afterglow from shocked circumstellar material. While both components are extremely luminous in known GRBs, a variety of scenarios predict the existence of luminous afterglow emission with little or no associated high-energy prompt emission. We present AT 2019pim, the first spectroscopically confirmed afterglow with no observed high-energy emission to be identified. Serendipitously discovered during follow-up observations of a gravitational-wave trigger and located in a contemporaneous *TESS* sector, it is hallmarked by a fast-rising ($t \approx 2$ h), luminous ($M_{UV,peak} \approx -24.4$ mag) optical transient with accompanying luminous X-ray and radio emission. No gamma-ray emission consistent with the time and location of the transient was detected by *Fermi*-GBM or by *Konus*, placing constraining limits on an accompanying GRB. We investigate several independent observational aspects of the afterglow in the context of constraints on relativistic motion and find all of them are consistent with an initial Lorentz factor of $\Gamma_0 \approx 10$ –30 for the on-axis material, significantly lower than in any well-observed GRB and consistent with the theoretically predicted ‘dirty fireball’ scenario in which the high-energy prompt emission is stifled by pair production. However, we cannot rule out a structured jet model in which only the line-of-sight material was ejected at low- Γ , off-axis from a classical high- Γ jet core, and an on-axis GRB with below-average gamma-ray efficiency also remains a possibility. This event represents a milestone in orphan afterglow searches, demonstrating that luminous optical afterglows lacking detected GRB counterparts can be identified and spectroscopically confirmed in real time.

Key words: relativistic processes – gamma-ray bursts – radio continuum: transients.

1 INTRODUCTION

Long-duration gamma-ray bursts (GRBs) originate from the collapse of a rapidly rotating stripped-envelope massive star. During the collapse, both a highly collimated relativistic jet and a largely isotropic supernova (SN) explosion are produced; the collision of the jet with the surrounding medium also produces a multiwavelength afterglow (for reviews see e.g. van Paradijs, Kouveliotou & Wijers 2000; Piran 2004; Woosley & Bloom 2006; Gehrels & Mészáros 2012; Hjorth & Bloom 2012).

The properties of the SN show little variation from event to event (Cano 2014; Melandri et al. 2014b; Cano et al. 2017). All known GRB-associated supernovae (SNe) are of spectral type Ic-BL; the SN peak luminosity varies by only about a factor of 2–3 and the rise time varies even less, suggesting a common progenitor with relatively little intrinsic diversity in (for example) structure or composition.¹

¹Known exceptions are plausibly associated with other classes of events: a few GRBs with $t_{90} > 2$ s but with strong upper limits on an accompanying classical SN (GRBs 060605, 060614, 211211A, and 230307A; Della Valle et al. 2006; Fynbo et al. 2006; Gehrels et al. 2006; Rastinejad et al. 2022; Troja et al. 2022; Levan et al. 2023) may be related to short-duration GRBs or perhaps another class of event entirely (Gal-Yam et al. 2006; Ofek et al. 2007; Zhang et al. 2007; Jin et al. 2015; Yang et al. 2022, 2024), while GRB

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The nature of the jet, however, is vastly more diverse. Inferred GRB isotropic-equivalent gamma-ray energies ($E_{\gamma, \text{iso}}$) vary from 10^{46} to almost 10^{55} erg, while the duration, spectral hardness, and temporal structure of the GRB light curve also vary greatly (Kouveliotou et al. 1993; Paciesas et al. 1999; Amati 2006). Some of this variation may originate from simple differences in orientation angle (a ‘structured jet’; e.g. Mészáros, Rees & Wijers 1998; Dai & Gou 2001; Lipunov, Postnov & Prokhorov 2001; Rossi, Lazzati & Rees 2002; Zhang & Mészáros 2002; Granot & Kumar 2003), although to what extent intrinsic versus viewing angle effects govern the observed diversity remains a subject of debate (e.g. Kulkarni et al. 1998; Soderberg et al. 2004; Lamb, Donaghy & Graziani 2005; Amati et al. 2007; Cenko et al. 2010, 2011; Pescalli et al. 2015; Salafia et al. 2015; Beniamini et al. 2020; Salafia et al. 2020; Salafia & Ghirlanda 2022; O’Connor et al. 2023).

GRBs are by definition selected at high photon energies (> 10 keV) via the detection of prompt emission by an orbiting wide-field-of-view satellite, which is then followed by a narrow-field search for the associated afterglow and/or SN. However, there is no strong reason to expect that all energetic jet outflows must produce luminous gamma-ray emission of this nature. The outflow might, for example, be insufficiently variable to generate the luminous internal shocks that are generally presumed to produce GRB prompt emission (Rees & Meszaros 1994). Alternatively, the velocity of the ejecta may be sufficiently low that pair production suppresses the production of the highest-energy photons (a ‘dirty’ fireball; Dermer, Chiang & Mitman 2000; Huang, Dai & Lu 2002; Rhoads 2003). Geometrical reasons may also be important: the GRB ejecta that produce the prompt emission travel much faster (and beam radiation into a narrower opening angle) than the afterglow, which by definition is only set up once the outflow has decelerated somewhat (Rhoads 1997; Perna & Loeb 1998; Granot et al. 2002; Nakar, Piran & Granot 2002; Rhoads 2003). The rate of these various types of gamma-ray-‘dark’ explosions may greatly exceed that of classical long-duration GRBs.

Finding examples has, however, proven quite challenging. The optical, X-ray, and radio sky are all much more crowded than the gamma-ray sky, requiring the advent of both wide-field telescopes and sophisticated machine-learning techniques to distinguish genuine transients. There are also many false positives with similar ‘fast-rise, slow-decay’ features. In the optical band, flares from M-dwarfs and cataclysmic variables (dwarf novae) are particularly problematic (Kulkarni & Rau 2006; Rau et al. 2008; Berger et al. 2013; Ho et al. 2018; Andreoni et al. 2020): at typical operational flux limits, the rates of these events exceed the expected rate of afterglows by orders of magnitude.

However, the past ten years have seen steady progress. The first optical orphan² afterglow candidate was PTF11agg (Cenko et al. 2013), found by the Palomar Transient Factory during a dedicated high-cadence narrow-field experiment. PTF11agg was detected as a new bright ($r \lesssim 18.25$ mag) transient in the first exposure of the field taken that night, and faded rapidly in subsequent exposures over the next few hours. Follow-up observations with the Karl G. Jansky Very Large Array (VLA; Perley et al. 2011) revealed a long-lived scintillating radio counterpart; deep late-time optical imaging after the optical transient faded unveiled a faint blue extended object at the location – most likely a high-redshift ($z \gtrsim 0.5$) host galaxy,

although its actual redshift remains unknown and its cosmological nature unconfirmed. Unfortunately, because of poor constraints on the true explosion time (a window of 20 h between the most recent limit and first detection), it was not possible to rule out that the location was in a ‘blind spot’ to *Fermi* and/or other satellites at the time of explosion.

Two other optical afterglows were subsequently discovered by wide-area sky surveys in a similar manner: iPTF14yb (Cenko et al. 2015) and ATLAS17aeu (Bhalerao et al. 2017; Stalder et al. 2017; Melandri et al. 2019). iPTF14yb was spectroscopically confirmed to originate at a cosmological distance (redshift $z = 1.9733$). ATLAS17aeu, discovered serendipitously in follow-up observations of a gravitational-wave trigger, also likely originated at $z > 1$ given the photometric properties of its presumptive host galaxy, although (as with PTF11agg) it has not been possible to confirm this spectroscopically. However, both events were later found to have associated GRBs detected by *Fermi* or other satellites whose times and sky locations were consistent with the optically discovered afterglows.

Dedicated afterglow searches with the Zwicky Transient Facility (ZTF) have yielded nine published³ afterglow candidates to date (Ho et al. 2020; Andreoni et al. 2021, 2022; Ho et al. 2022) of which seven have redshift measurements from optical spectroscopy. Redshifts range from $z = 0.876$ (AT 2021buv; Ho et al. 2022) to $z = 2.9$ (AT 2020bbl; Ho et al. 2020). Of the nine events, three had no associated detected GRB (AT 2020bbl, AT 2021any, and AT 2021lfa). However, at the redshifts of these three events, an accompanying typical GRB cannot be ruled out based on the sensitivity and coverage of GRB satellites (Ho et al. 2020, 2022; but see Lipunov et al. 2022 who refine the explosion time of AT 2021lfa and present deeper limits on gamma-ray emission that are more constraining). As a result, it is unclear from the ZTF observations alone if these objects represent normal GRBs whose prompt high-energy emission was simply missed. Modelling the X-ray through radio emission, and the detection of a ‘rise phase’ using the MASTER telescope network, has led to suggestions that at least some of these events had a truly low Lorentz factor (Lipunov et al. 2022; Xu, Huang & Geng 2023), and that another may represent a GRB with a low gamma-ray efficiency (Sarin et al. 2022).

Advancements have also been made outside the optical domain. An X-ray transient with GRB-like properties and no known GRB counterpart was reported by Bauer et al. (2017), although it is much lower in luminosity than classical GRB afterglows and is also spectroscopically unconfirmed (but is convincingly associated with a high-redshift galaxy with photo- z of $2.23_{-1.84}^{+0.98}$). Separately, searches for orphan afterglows using radio-survey data have identified a compelling candidate radio afterglow, plausibly from a highly off-axis GRB (Law et al. 2018), but the explosion time window is years long and it is not possible rule out a classical GRB origin. Additionally, radio follow-up observations of optically discovered SNe Ic-BL have identified a few with moderately luminous radio emission indicative of a very energetic high-velocity shock, although no clear evidence of a jetted relativistic outflow has yet emerged (Soderberg et al. 2010; Margutti et al. 2014; Corsi et al. 2017; Marongiu et al. 2019).

In this paper, we describe the discovery of AT 2019pim (ZTF19abvzsw), the first unambiguous optical afterglow of a

111209A and its unusually luminous SN is a member of the ultra-long class of GRBs (Gendre et al. 2013; Levan et al. 2014; Greiner et al. 2015).

²We use the term ‘orphan’ to describe any afterglow without an observationally associated GRB.

³This total does not include several other events distributed via GCN Circulars but not yet published, including the notable events AT 2023lcr (Swain et al. 2023) and AT 2023sva (Vail et al. 2023).

relativistic explosion with secure limits on accompanying GRB-like high-energy emission. In Section 2, we briefly outline the ZTF afterglow search programme and the partially serendipitous discovery of AT2019pim during a gravitational-wave counterpart search, and describe our observational follow-up activities that confirmed this source as an afterglow. We model the observational properties in Section 3, including the explosion time and peak time using a combination of our ZTF discovery observations, follow-up observations, and *TESS* data, and we place upper limits on associated gamma-ray emission from *Konus* and *Fermi*. Section 4 establishes physical constraints on the nature of the outflow using the combined optical and radio data set, and we summarize our conclusions in Section 5.

2 OBSERVATIONS

2.1 P48 Discovery

The Zwicky Transient Facility (ZTF; Graham et al. 2019; Bellm et al. 2019a) is a refurbishment of the Palomar 48-inch Oschin Schmidt telescope (P48), most recently in use as part of the Palomar Transient Factory (PTF). The ZTF camera has a 47 square degree operational field of view, fast readout, and near-real-time data processing (Masci et al. 2019; Dekany et al. 2020).

A major science driver of ZTF has been the search for luminous, fast, and/or young transients (characteristic time-scales < 1 d). While such transients can be detected in the standard 2–3 d cadence public survey (Bellm et al. 2019b), higher-cadence observations (nightly or faster cadence) are better suited for rapid and accurate identification of these objects. Several ZTF programmes operate at higher cadence, including a 10 000 square degree ‘partnership’ survey which acquires 4 observations of each field per night and a 2000–3000 deg² 1-night cadence survey. During 2019 and 2020, ZTF also conducted a public 1-night cadence survey shadowing the *Transiting Exoplanets Survey Satellite* (*TESS*; Ricker et al. 2015) footprint (van Roestel et al. 2019). Custom software filters scan all of these streams to search for bright new transients not coincident with known point sources.

On 2019 September 1 (23:31:01.838 UTC⁴; equivalent to 58727.97988 MJD), the Laser Interferometer Gravitational-wave Observatory (LIGO)–Virgo Gravitational Wave Interferometer (Virgo) network (Acernese et al. 2015; Abbott et al. 2018) registered a candidate gravitational-wave signal, initially designated S190901ap (LIGO Scientific Collaboration and Virgo Collaboration 2019), consistent with a neutron-star–neutron-star merger waveform.⁵ Only LIGO L1/Livingston detected the event (H1/Hanford was offline) and thus the localization was exceptionally poor, covering over 14 000 deg²; the distance constraint is 241 ± 79 Mpc ($z = 0.054 \pm 0.017$).⁶ Nevertheless, ZTF was triggered in target-of-opportunity mode for the following night to tile as much of the observable error region as possible and all candidates detected during the night with no previous history were scanned by eye using tools available via the GROWTH Marshal (Kasliwal et al. 2019).

AT2019pim was first detected in ZTF data at MJD = 58728.1798 with a magnitude⁷ of $g = 20.04 \pm 0.16$. Following a filter change,

the source was detected again ~ 1 h later (MJD = 58728.2300) with $r = 19.45 \pm 0.11$ mag at a consistent location ($\alpha = 18^{\text{h}}37^{\text{m}}53.48^{\text{s}}$, $\delta = +61^{\circ}29'52.74''$; J2000). There is no counterpart in prior ZTF reference imaging nor any previous detections of variability at the same location. The most recent non-detection originates from the preceding night (5σ limit of $g > 20.60$ mag at MJD = 58727.3161). The source was within the *TESS* footprint and the associated footprint of the public ZTF 1-night *TESS* shadowing survey, but the alerts it generated did not enter the public stream because the gravitational wave target-of-opportunity search programme displaced normal public observations that night. It passed an automated software filter designed to find young SNe and was ‘saved’ (i.e. flagged as a transient of interest) after scanning the output of this and other filters for candidate counterparts of the GW event. The transient was reported to the GCN Circulars (as ZTF19abvizsw, its internal ZTF survey name), along with the three other transients detected that night consistent within the error region with no prior history (Kool et al. 2019). All four candidates were reported to the Transient Name Server the next day (Fremling 2019).

2.2 Spectroscopy

On the night following the discovery of the transient (2019-09-03), we obtained a spectrum using the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck I 10 m telescope. The 600/4000 grism was used on the blue side and the 600/7500 grating was used on the red side, providing wavelength coverage of 3139–5642 Å (blue) and 6236–9516 Å (red). The 1 arcsec slit was used, positioned at the parallactic angle (134 deg at the time of observation). The exposure time was 600 s on both sides. The spectrum was reduced using LPipe (Perley 2019) with BD+28 4211 as a flux calibrator. The red and blue relative flux scales are scaled by matching synthetic photometry to colours inferred from photometry of the transient.

The reduced spectrum, shown in Fig. 1, is largely featureless and fairly red. Deep narrow absorption lines are evident in the middle region of the spectrum; these are matched by Fe II, Mg II, and Mg I at a common redshift of $z = 1.2592 \pm 0.0004$. Because the signal-to-noise ratio (S/N) of the spectrum does not permit the detection of fine-structure lines, this is technically only a lower limit on the true redshift. A firm upper limit of $z < 2.2$ can be placed by the absence of Lyman α at $\lambda > 3900$ Å, where the S/N of the spectrum is relatively high. In spite of this, we can be reasonably confident that the absorption redshift is indeed that of AT2019pim: the strength of the absorption lines (in particular of the MgII 2796 line, for which we measure a rest-frame equivalent width of $W_r = 4.0 \pm 0.3$ Å) is much higher than in typical line-of-sight absorbers (Christensen et al. 2017; Churchill et al. 2020), and our spectrum rules out any strong ($W_r \gtrsim 1$ Å) higher-redshift Mg II absorption system between $1.26 < z < 2.2$. We will assume $z = 1.2592$ throughout this work.

The implied rest-frame UV magnitude (AB) at the time of the g -band discovery is $M_{2170\text{Å}} = -24.4$ (for $z = 1.2596$, as will be assumed throughout the remainder of this paper). This unambiguously identifies the event as an extremely luminous cosmological explosion and (given the inconsistent distances) firmly rules out any association with the gravitational-wave trigger.

2.3 Follow-up photometry

We used several different telescopes at locations around the globe to obtain additional photometric observations of AT2019pim over the first few nights following its discovery. These include the GROWTH

⁴UT dates are used throughout this paper.

⁵The astrophysical nature of this event has not been confirmed by further analysis (Abbott et al. 2021).

⁶We assume $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$ throughout this work.

⁷Magnitudes are in the AB system (Oke & Gunn 1983) and uncertainties are 1σ throughout, unless otherwise specified.

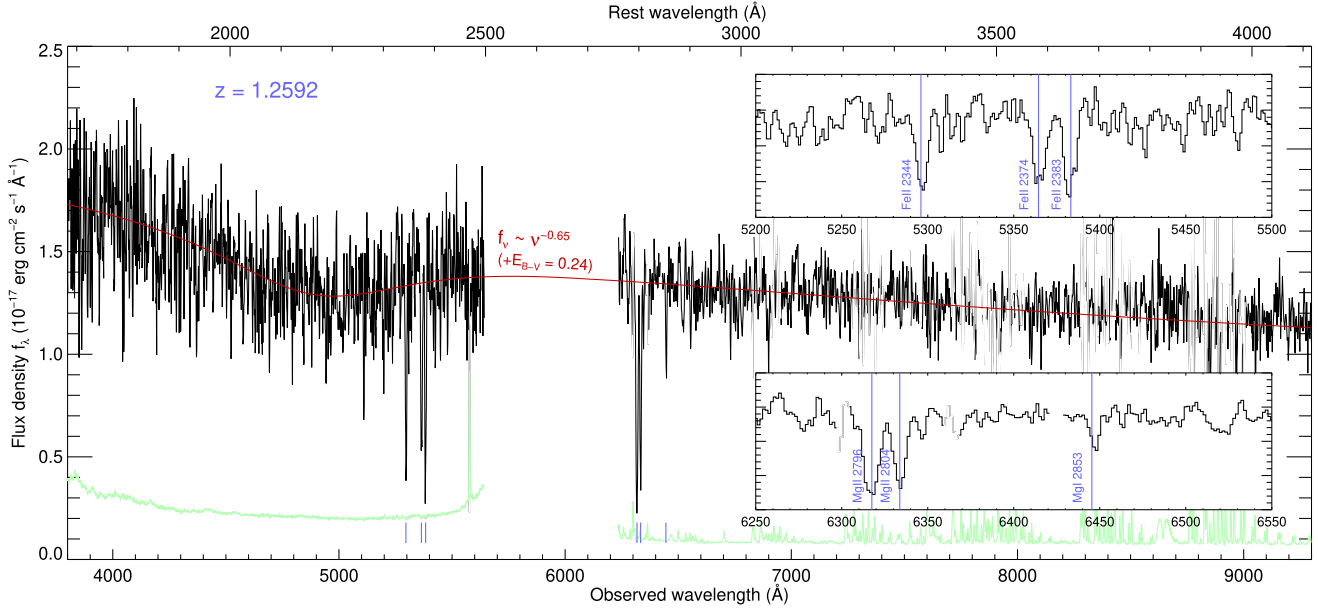


Figure 1. LRIS spectrum of AT 2019pim. The spectrum has been lightly smoothed by convolution, and regions affected by strong night-sky lines are plotted in grey. A continuum model is overplotted in dark red: this is a power law ($F_\nu \propto \nu^{-0.65}$) extinguished by host-galaxy dust ($E_{B-V} = 0.24$ mag, using a Fitzpatrick 1999 dust model with $R_V = 3.1$ and $c_3 = 1.0$) and Galactic dust ($E_{B-V} = 0.038$ mag). Inset panels show zoom-ins on two strong-line regions: the Fe II series (upper panel) and the Mg II/Mg I series (lower panel). The error spectrum (after convolution) is shown in light green.

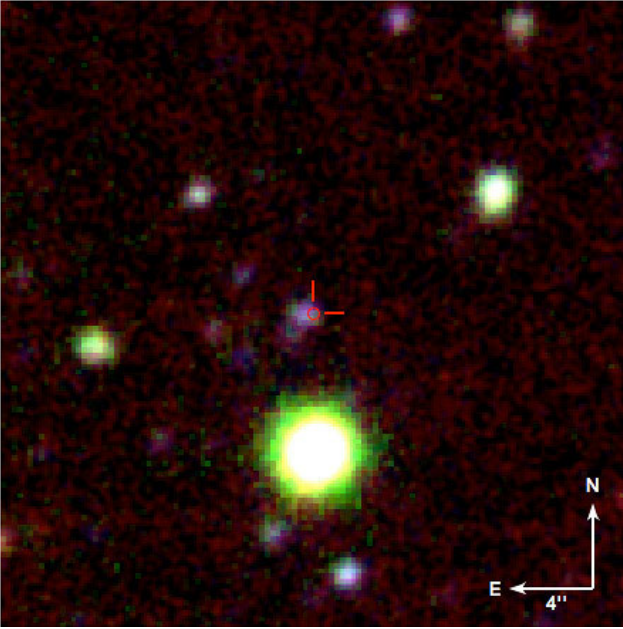


Figure 2. Late-time imaging from LRIS (g , i) and GTC (r), combined into a false-colour image. The image is 30 arcsec across. The afterglow location, shown at centre, is coincident with a blue, extended source, also seen in (shallower) Legacy Survey imaging of the field.

India Telescope (GIT; Kumar et al. 2022), the Liverpool Telescope (LT), and the Apache Point Observatory 3 m telescope (APO). We additionally acquired later imaging observations of the transient with ACAM on the William Herschel Telescope (2019-09-11/12), with LRIS on the Keck I 10 m telescope (2019-09-24 and 2019-10-27), and with OSIRIS on the GTC (2019-11-23). Late-time reference

imaging of the host galaxy was taken with LRIS in April 2022 using the LRIS U , G , R , and $RG850$ filters.

Photometry for most follow-up observations was performed using a custom aperture photometry routine in IDL, with calibration performed relative to Sloan Digital Sky Survey (SDSS) secondary standard stars in the field.

The host galaxy of this source (shown in Fig. 2) is relatively bright and contributes non-negligibly to the flux at all epochs. For most of our measurements, we correct for the host contribution in flux space by measuring the host flux in the late-time LRIS imaging (U , G , R , and $RG850$ were treated as u_{SDSS} , g_{SDSS} , R_C , and z_{SDSS} , respectively) and GTC imaging⁸ (r_{SDSS}) and subtracting the fluxes from the direct aperture photometry measurements. No reference imaging was acquired in the i band, so the host flux at this band was inferred indirectly via synthetic photometry of our fit to the host spectral energy distribution (SED). The host-galaxy magnitudes are given in Table 1.

While the host galaxy is compact and direct flux subtraction should generally be adequate, in the case of the LRIS measurements in September and October we employ image subtraction to obtain the flux of the afterglow above the level of the host galaxy. This was not possible for the simultaneous LRIS i -band observations, since no late-time reference image was obtained in this band. The last epoch resulted in non-detections in both bands; upper limits are for an aperture fixed at the afterglow location and given as 2.5σ . Photometry is presented in Table 2.

⁸The GTC observations were taken 83 d post-explosion, when afterglow contribution may still have been present. Our empirical model (Section 3.2) suggests that the afterglow had $r \approx 27.5$ mag at this time, which would represent about 0.06 mag contribution to the host measurement. This is less than the 1σ statistical uncertainty in the photometry, and we did not correct for this in our estimate in Table 1.

Table 1. Host photometry.

| filter | AB magnitude |
|----------|----------------------|
| <i>u</i> | 24.63 ± 0.09 |
| <i>g</i> | 24.29 ± 0.07 |
| <i>r</i> | 24.50 ± 0.15 |
| <i>R</i> | 24.20 ± 0.06 |
| <i>i</i> | (24.08) [†] |
| <i>z</i> | 23.38 ± 0.09 |

Note. [†]Estimated using SED fitting (Section 3.5)

Table 2. Ground-based photometry of AT2019pim.

| facility | MJD | filter | AB mag. | unc. |
|--------------|------------|----------|---------|----------|
| P48 + ZTF | 58727.1641 | <i>g</i> | >20.74 | <i>a</i> |
| P48 + ZTF | 58727.1790 | <i>g</i> | >20.77 | <i>a</i> |
| P48 + ZTF | 58727.2708 | <i>g</i> | >20.64 | <i>a</i> |
| P48 + ZTF | 58727.2933 | <i>r</i> | >20.49 | <i>a</i> |
| P48 + ZTF | 58727.3161 | <i>g</i> | >20.60 | <i>a</i> |
| P48 + ZTF | 58728.1798 | <i>g</i> | 20.04 | 0.16 |
| P48 + ZTF | 58728.2297 | <i>r</i> | 19.45 | 0.11 |
| GIT | 58728.6034 | <i>r</i> | 20.34 | 0.09 |
| GIT | 58728.6100 | <i>r</i> | 20.35 | 0.06 |
| GIT | 58728.6189 | <i>i</i> | 20.12 | 0.09 |
| GIT | 58728.6259 | <i>i</i> | 19.97 | 0.08 |
| GIT | 58728.6353 | <i>r</i> | 20.40 | 0.08 |
| GIT | 58728.7223 | <i>i</i> | 19.96 | 0.08 |
| GIT | 58728.7287 | <i>i</i> | 20.09 | 0.09 |
| GIT | 58728.8026 | <i>g</i> | 21.23 | 0.11 |
| GIT | 58728.8093 | <i>g</i> | 21.07 | 0.10 |
| LT + IOO | 58729.8552 | <i>r</i> | 21.54 | 0.18 |
| LT + IOO | 58729.9420 | <i>r</i> | 21.70 | 0.09 |
| LT + IOO | 58729.9481 | <i>g</i> | 22.16 | 0.10 |
| LT + IOO | 58729.9541 | <i>i</i> | 21.24 | 0.07 |
| LT + IOO | 58729.9621 | <i>z</i> | 20.96 | 0.12 |
| LT + IOO | 58730.8802 | <i>r</i> | 22.17 | 0.10 |
| LT + IOO | 58730.8862 | <i>g</i> | 22.73 | 0.21 |
| LT + IOO | 58730.8923 | <i>i</i> | 21.72 | 0.10 |
| LT + IOO | 58730.8983 | <i>z</i> | 21.33 | 0.19 |
| LT + IOO | 58731.0112 | <i>r</i> | 22.23 | 0.12 |
| LT + IOO | 58731.0172 | <i>g</i> | 22.78 | 0.17 |
| LT + IOO | 58731.0232 | <i>i</i> | 21.76 | 0.11 |
| LT + IOO | 58731.0293 | <i>z</i> | 21.75 | 0.22 |
| APO | 58733.2200 | <i>r</i> | 22.36 | 0.03 |
| APO | 58733.2530 | <i>i</i> | 21.94 | 0.05 |
| APO | 58733.2650 | <i>g</i> | 22.78 | 0.11 |
| WHT + ACAM | 58737.8819 | <i>r</i> | 22.77 | 0.10 |
| WHT + ACAM | 58738.8839 | <i>i</i> | 22.55 | 0.09 |
| WHT + ACAM | 58739.9939 | <i>i</i> | 22.67 | 0.13 |
| WHT + ACAM | 58740.0219 | <i>r</i> | 23.48 | 0.27 |
| Keck1 + LRIS | 58750.2351 | <i>g</i> | 25.44 | 0.36 |
| Keck1 + LRIS | 58750.2354 | <i>i</i> | 25.50 | 0.63 |
| Keck1 + LRIS | 58783.2306 | <i>i</i> | >24.66 | <i>b</i> |
| Keck1 + LRIS | 58783.2306 | <i>g</i> | >26.22 | <i>b</i> |

Notes. ^aZTF limits are 5 σ alert-photometry limits for the associated image.

^bLRIS limits are 2.5 σ forced photometry limits at the source location.

2.4 TESS observations

As previously noted, AT2019pim was detected in a high-cadence ZTF field associated with an active *TESS* sector. *TESS* observed the field nearly continuously during Sector 15 from 2019-08-15 to 2019-09-10 in Camera 2, CCD 2. The location was imaged in nearly 2400 30 min full-frame images (FFIs) over that period.

A light curve for AT2019pim was constructed from the FFIs using difference imaging. First, we constructed a reference image by median stacking 20 FFIs with low background levels (Fig. 3). We then subtracted the reference image from each epoch using the ISIS software (Alard & Lupton 1998; Alard 2000), which solves for a spatially variable kernel that matches the point-spread function (PSF) of the reference image to individual FFIs. This procedure removes systematic errors due to pointing shifts/jitter and thermal variations, and is able to recover clear but weak detections of the transient in individual images. We extracted a light curve by fitting a model of the PSF to the difference images at the predicted location of the transient in the FFIs based on the coordinates of AT2019pim, and subtracted a local background based on the median of pixel values in an annulus of inner/outer radius 8/12 pixels, following similar procedures as by Fausnaugh et al. (2021, 2023).

Despite background subtraction and PSF-fitting, the long-term light curve shows slow (~ 1 d), low-level ($\sim 10 \mu\text{Jy}$) variations in the baseline flux. The origin of this is not completely certain, but is likely due to a combination of real variation in nearby bright stars that are blended with the transient and its background annulus, and (particularly in the days after the afterglow onset) variations in the background as the Earth limb becomes visible to the spacecraft. To model these background estimations, we first subtracted a model of the late-time afterglow flux based on ground-based data (Section 3.2), then measured the remaining background flux using a series of median windows with a duration of 0.5 d each spanning from 3 d prior to the likely explosion time to 3 d after, excluding a 1 d region around the afterglow onset. A fourth-order polynomial was then fit to the median-averaged data, and the resulting background model was subtracted from the raw count values to estimate the afterglow count rate.

The photon-counting uncertainties in the count measurements substantially underestimate the actual variation from exposure to exposure, even on short time-scales when no background or afterglow variation is expected. We calculated corrected errors by taking the standard deviation of the afterglow- and background-subtracted flux over each of the median windows described above and fit this with a second-order polynomial to model the time dependence of the noise.

TESS count values are converted to flux-density values (at the *TESS* central wavelength of $\lambda = 7865 \text{ \AA}$) using a conversion factor of $0.01208 \mu\text{Jy count}^{-1}$, calculated assuming a standard (Vega-like) spectrum and an on-source integration time of $(1800 \text{ s}) \times (0.8) \times (0.99) = 1425.6 \text{ s}$ per FFI exposure.⁹

The *TESS* light curve is given in Table 3. The counts column provides values prior to any background subtraction; the flux column lists values after background subtraction. Observations taken more than 0.2 d before or after the probable explosion time were binned together in proportion to the time before or after explosion.

2.5 Limits on a GRB counterpart

We searched the *Fermi*¹⁰ (Gruber et al. 2014; von Kienlin et al. 2014; Narayana Bhat et al. 2016), *Fermi* subthreshold¹¹ (with reliability flag != 2), *Swift*¹², and General Coordinates Network¹³ archives for a

⁹The ~ 20 percent reduction in effective integration time is a consequence of the on-board cosmic ray excision procedure (Vanderspek et al. 2018).

¹⁰<https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html>

¹¹https://gcn.gsfc.nasa.gov/fermi_gbm_subthresh_archive.html

¹²https://swift.gsfc.nasa.gov/archive/grb_table/

¹³https://gcn.gsfc.nasa.gov/gcn3_archive.html

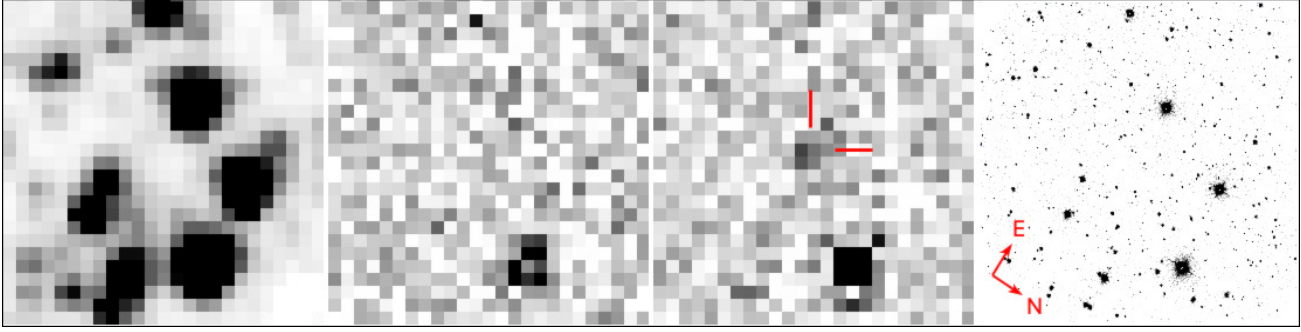


Figure 3. *TESS* imaging of AT 2019pim. The left panel shows a stacked pre-explosion image of the field. The two middle panels display individual FFIs after subtraction of this reference. The middle-left panel is from an FFI taken at TJD 1728.5004505, ~ 0.1 d before the inferred onset time; the detected object near the bottom is a bright variable star in the field. The middle-right panel is from an FFI taken at peak (TJD 1728.667117), showing the detection of the afterglow (marked). A Liverpool Telescope image is shown at right for reference. Images are 8.3 arcmin on each side.

Table 3. *TESS* photometry of AT 2019pim near the time of outburst.

| MJD ^a | Counts ^b | F_v^c (μJy) | σ^d (μJy) | n_{FFI}^e |
|------------------|---------------------|-------------------------------|----------------------------------|--------------------|
| 58727.74062 | -1215 | -6.58 | 12.58 | 3 |
| 58727.80312 | 207 | 11.25 | 12.63 | 3 |
| 58727.85520 | -1873 | -13.35 | 15.52 | 2 |
| 58727.89688 | -1425 | -7.51 | 15.56 | 2 |
| 58727.93854 | -411 | 5.17 | 15.59 | 2 |
| 58727.98020 | -555 | 3.86 | 15.63 | 2 |
| 58728.02188 | 260 | 14.12 | 15.67 | 2 |
| 58728.05312 | -1055 | -1.45 | 22.20 | 1 |
| 58728.07396 | 387 | 16.19 | 22.22 | 1 |
| 58728.09479 | -2752 | -21.54 | 22.25 | 1 |
| 58728.11562 | -524 | 5.59 | 22.28 | 1 |
| 58728.13646 | 448 | 17.54 | 22.30 | 1 |
| 58728.15729 | 3774 | 57.93 | 22.33 | 1 |
| 58728.17812 | 9708 | 129.81 | 22.35 | 1 |
| 58728.19895 | 8994 | 121.39 | 22.38 | 1 |
| 58728.21979 | 4562 | 68.06 | 22.40 | 1 |
| 58728.24062 | 5409 | 78.49 | 22.43 | 1 |
| 58728.26145 | 6813 | 95.65 | 22.45 | 1 |
| 58728.28229 | 6737 | 94.93 | 22.47 | 1 |
| 58728.30312 | 7242 | 101.22 | 22.50 | 1 |
| 58728.32395 | 6121 | 87.88 | 22.52 | 1 |
| 58728.34479 | 5487 | 80.41 | 22.55 | 1 |
| 58728.37603 | 3780 | 60.08 | 15.97 | 2 |
| 58728.41770 | 4082 | 64.11 | 16.00 | 2 |
| 58728.45937 | 2199 | 41.74 | 16.03 | 2 |
| 58728.50103 | 4200 | 66.26 | 16.07 | 2 |
| 58728.55312 | 4604 | 71.59 | 13.15 | 3 |
| 58728.61562 | 3785 | 62.21 | 13.19 | 3 |
| 58728.67812 | 1384 | 33.70 | 13.23 | 3 |
| 58728.75451 | 1587 | 36.73 | 13.27 | 3 |
| 58728.83437 | 305 | 21.79 | 11.54 | 4 |
| 58728.92812 | 968 | 30.40 | 10.36 | 5 |
| 58729.03228 | 1402 | 36.23 | 10.40 | 5 |
| 58729.14687 | -404 | 14.95 | 9.54 | 6 |

Notes. ^aMidpoint of observation.

^b*TESS* counts, prior to subtraction of the time-dependent background model. (For binned rows, this is the mean counts per exposure.)

^c*TESS* flux density, after subtraction of the time-dependent background model. Not corrected for Galactic or host extinction.

^d*TESS* flux-density uncertainty, based on the noise model.

^e Number of exposures (FFIs) binned together.

Note. This table includes only measurements close to the inferred onset time of the afterglow. A complete table of all *TESS* measurements with no binning applied is provided in the online supplementary material.

GRB between the last ZTF non-detection and the first ZTF detection. The only event that occurred during this period was the known GRB 190901A, at MJD 58727.89015. The position of this GRB is inconsistent with that of AT 2019pim and its time of occurrence was several hours before the optical explosion-time window (Section 3.1), so an association can be firmly ruled out.

The position of AT 2019pim was in the field of view of the *Fermi* Gamma-Ray Burst Monitor (GBM; Meegan et al. 2009) throughout the period between the most recent ZTF upper limit and ZTF discovery except for brief Earth occultations and South Atlantic Anomaly (SAA) passages. We ran the GBM targeted search in the 10–1000 keV energy band during this period. The detector count data was separated into 1 min blocks, each of which was analysed on 1 and 8 s sliding time windows and, assuming a spectral model (described below), checked for detector-coherent flux above the background level.

Limits were calculated for two different search time-scales (1.024 and 8.192 s) and three different spectral models, shown in Fig. 4. Our preferred spectral model is parametrized using a Band (2003) function with $E_{\text{peak}} = 230$ keV, $\alpha = -1.0$, $\beta = -2.3$, and is shown as a black curve, although for comparison, we also provide limits assuming two other models: a ‘soft’ model assuming a Band spectrum and $E_{\text{peak}} = 70$ keV, $\alpha = -1.9$, $\beta = -3.7$, and a ‘hard’ model with a cutoff power law (Goldstein et al. 2016) and $E_{\text{peak}} = 1500$ keV, $\alpha = -1.5$. For the preferred model¹⁴, the typical limit on the 1 s peak flux during the optical explosion time window is $F < 9 \times 10^{-8}$ erg cm⁻² s⁻¹, equivalent to a limit on the peak luminosity of $L_{\text{iso,peak}} < 8 \times 10^{50}$ erg s⁻¹. For 8.192 s intervals, the limit on the average flux is $< 3 \times 10^{-8}$ erg cm⁻² s⁻¹, equivalent to $L_{\text{iso,peak}} < 2.8 \times 10^{50}$ erg s⁻¹.

To convert these values to approximate limits on the burst fluence, we take the 8 s flux limit and multiply by the assumed characteristic (observed) time-scale, typically 40 s for long-duration GRBs. We obtain $S < 1.2 \times 10^{-6}$ erg cm⁻², equivalent to $E_{\text{iso}} < 5 \times 10^{51}$ erg.

Fermi was occulted in the direction of AT 2019pim for about 20 min at the beginning of the afterglow-inferred explosion window and about 40 min towards the end of the window, so no limit can be placed on gamma-ray emission during these periods from GBM. However, the Interplanetary Network was sensitive to the position

¹⁴For the ‘hard’ spectral model the limit would be shallower by a factor of ~ 2 , although given the $E_{\text{peak}}-E_{\text{iso}}$ relation Amati (2006) a spectrally hard burst at $z = 1.29$ would be expected to also be very luminous.

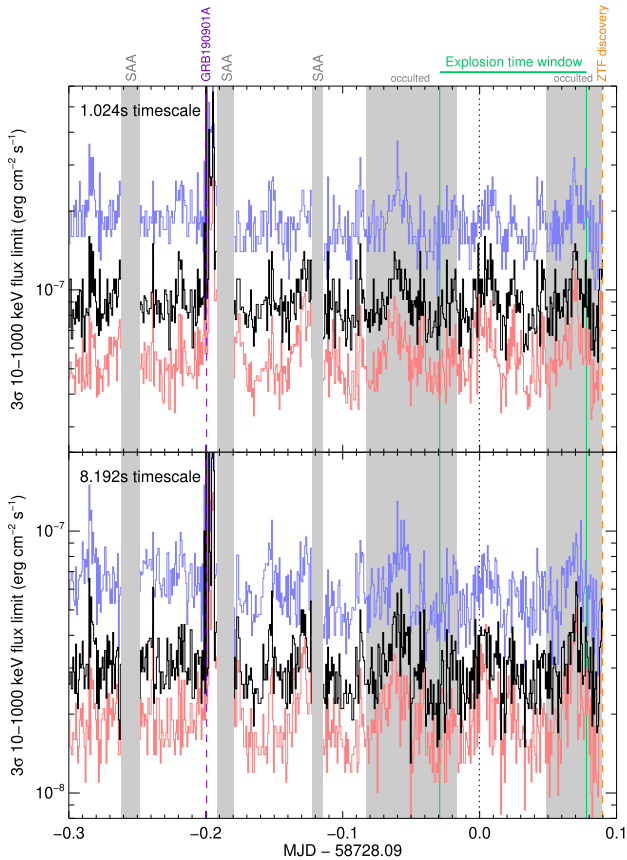


Figure 4. *Fermi* GBM limits on gamma-ray emission (10–1000 keV) near the time of onset of AT 2019pim. The black curves show limits assuming a standard GRB spectrum of $E_{\text{peak}} = 230$ keV; the red curves assume a soft spectrum ($E_{\text{peak}} = 70$ keV), and the blue curves assume a hard spectrum ($E_{\text{peak}} = 1500$ keV). The upper panel shows limits on the flux averaged over 1 s intervals and the bottom panel over 8 s intervals. Limits are calculated in 1 min windows and are 3σ . SAA passages and occultations are indicated as shaded regions. The explosion-time window as inferred from modelling of the optical rise is indicated (Section 3.1).

of AT 2019pim throughout the inferred explosion window, and no detections are recorded.

From the *Konus-Wind* observations, using the same spectral model as for the GBM upper limit calculations, the 90 percent confidence limiting peak flux (10–1000 keV, 2.944 s time-scale) is 1.5×10^{-7} erg cm $^{-2}$ s $^{-1}$, equivalent to $L_{\text{iso,peak}} < 4.4 \times 10^{51}$ erg s $^{-1}$. Assuming a similar scaling over longer intervals as in GBM, the equivalent E_{iso} limit is about $E_{\text{iso}} < 3.6 \times 10^{52}$ erg.

The position of AT 2019pim was not¹⁵ in the field of view of the *Swift* Burst Alert Telescope (BAT; Barthelmy 2005), except for during short windows.

2.6 *Swift* XRT observations

We obtained two 3 ks observations with the X-Ray Telescope (XRT; Burrows et al. 2005) on board the *Neil Gehrels Swift Observatory* (*Swift*; Gehrels et al. 2004) under a target-of-opportunity program (target ID 11549). The first observation started on Sept 4.13, and the

second started on Sept 12.08. Using the online tool¹⁶ from the *Swift* team (Evans et al. 2007, 2009), we found that the count rate in the first observation was 0.021 ± 0.003 s $^{-1}$ with a best-fitting photon index of $\Gamma = 1.8^{+0.8}_{-0.6}$ and a corresponding unabsorbed flux density of $f_X = 8.6^{+4.6}_{-2.5} \times 10^{-13}$ erg cm $^{-2}$ s $^{-1}$ (90 percent confidence), and $L_X = 2.5^{+1.4}_{-0.7} \times 10^{46}$ erg s $^{-1}$ (Ho et al. 2019). This assumes a neutral hydrogen column density $n_H = 5.6 \times 10^{20}$ cm $^{-2}$ (Willingale et al. 2013). In the second observation, the count rate was 0.003 ± 0.001 s $^{-1}$. Assuming the same photon index ($\Gamma = 1.8$) and n_H we used *webpimms*¹⁷ to find $f_X = (1.3 \pm 0.5) \times 10^{-13}$ erg cm $^{-2}$ s $^{-1}$ and $L_X = (3.8 \pm 1.5) \times 10^{45}$ erg s $^{-1}$.

2.7 Radio observations

Shortly after the spectroscopic confirmation of the transient, we triggered our pre-approved VLA programme for follow-up observations of orphan afterglows (programme ID VLA/18B-242, PI D. Perley). The transient was well detected in the initial X-band observation and mag in the observed optical bands. We continued following it with a series of observations at *L*, *S*, *C*, *X*, and *Ku* bands during the 2019B A-configuration cycle. Observations in different bands were not always obtained at the same epoch owing to scheduling constraints. Late-time observations were obtained in 2020 via dedicated follow-up programmes (IDs VLA/19B-342 and VLA/20A-506, PI D. Perley). This included a D-configuration observation in *C*, *X*, and *Ku* bands in January 2020, a C-configuration observation in *X* and *Ku* bands in 2020 April, and a final deep ($t_{\text{int}} = 2.15$ h) C-configuration observation in *X* band in 2020 June. The D-configuration *C*-band observations were significantly affected by radio frequency interference (RFI), as were the April C-configuration *X*-band observations above 10 GHz.

Data reduction was performed using standard procedures in the Astronomical Image Processing System (AIPS). Images were made in separate windows with a bandwidth of 1 GHz, except in the last two observations where images were made with a 2 GHz bandwidth. Flux-density measurements were performed using *jmfit*. In the small number of cases where the afterglow was not securely detected, the location of the centroid was fixed to the position as measured in our high-S/N A-configuration imaging to provide a forced measurement of the flux density. All values are reported in Table 4. Reported uncertainties do not include errors in the flux calibration, which is expected to be about 5 percent (or less) of each measurement. Light curve at a few select frequencies is shown in

We do not apply any corrections for radio emission from the host galaxy. The star-formation rate of the host as measured from optical SED fitting (Section 3.5) is about $3 M_{\odot}$ yr $^{-1}$, which (using the relations in Murphy et al. 2011) at the distance of AT2019pim would contribute only ~ 0.6 μ Jy of radio continuum flux at 1 GHz and less at higher frequencies, and so can safely be ignored.

3 EMPIRICAL MODELLING AND ANALYSIS

Before interpreting the emission physically, we first attempt to fit simple empirical models to constrain key features: specifically the explosion time, temporal and spectral slopes, and temporal and spectral breaks.

¹⁵Search conducted using https://github.com/lanl/swiftbat_python

¹⁶https://www.swift.ac.uk/user_objects/

¹⁷<https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl>

Table 4. VLA measurements of AT 2019pim.

| MJD | ν (GHz) | F_ν (μ Jy) | unc. (μ Jy) | MJD | ν (GHz) | F_ν (μ Jy) | unc. (μ Jy) |
|------------|----------------|------------------------|---------------------|------------|----------------|------------------------|---------------------|
| 58731.0379 | 8.50 | 25 | 9 | 58760.1055 | 5.50 | 340 | 9 |
| 58731.0379 | 9.50 | 52 | 8 | 58760.1055 | 6.50 | 451 | 9 |
| 58731.0379 | 10.50 | 93 | 9 | 58760.1055 | 7.50 | 434 | 9 |
| 58731.0379 | 11.50 | 103 | 10 | 58760.1278 | 8.50 | 345 | 9 |
| 58733.1521 | 8.50 | 183 | 9 | 58760.1278 | 9.50 | 314 | 9 |
| 58733.1521 | 9.50 | 158 | 9 | 58760.1278 | 10.50 | 298 | 9 |
| 58733.1521 | 10.50 | 139 | 15 | 58760.1278 | 11.50 | 293 | 10 |
| 58733.1521 | 11.50 | 178 | 15 | 58760.1535 | 12.50 | 253 | 10 |
| 58737.1719 | 8.50 | 237 | 9 | 58760.1535 | 13.50 | 246 | 9 |
| 58737.1719 | 9.50 | 233 | 8 | 58760.1535 | 14.50 | 257 | 10 |
| 58737.1719 | 10.50 | 239 | 12 | 58760.1535 | 15.50 | 253 | 10 |
| 58737.1719 | 11.50 | 248 | 12 | 58760.1535 | 16.50 | 243 | 11 |
| 58739.1205 | 2.25 | 0 | 30 | 58760.1535 | 17.50 | 266 | 13 |
| 58739.1205 | 2.75 | 154 | 16 | 58770.0915 | 1.02 | 29 | 54 |
| 58739.1205 | 3.25 | 163 | 12 | 58770.0915 | 1.28 | 193 | 35 |
| 58739.1205 | 3.75 | 143 | 12 | 58770.0915 | 1.52 | 188 | 46 |
| 58739.1430 | 8.50 | 146 | 9 | 58770.0915 | 1.78 | 245 | 38 |
| 58739.1430 | 9.50 | 157 | 8 | 58770.1140 | 2.25 | 131 | 19 |
| 58739.1430 | 10.50 | 178 | 9 | 58770.1140 | 2.75 | 141 | 15 |
| 58739.1430 | 11.50 | 212 | 10 | 58770.1140 | 3.25 | 119 | 12 |
| 58739.1684 | 12.50 | 265 | 10 | 58770.1140 | 3.75 | 108 | 12 |
| 58739.1684 | 13.50 | 243 | 9 | 58775.0573 | 8.50 | 161 | 7 |
| 58739.1684 | 14.50 | 280 | 10 | 58775.0573 | 9.50 | 169 | 7 |
| 58739.1684 | 15.50 | 265 | 10 | 58775.0573 | 10.50 | 166 | 7 |
| 58739.1684 | 16.50 | 315 | 11 | 58775.0573 | 11.50 | 129 | 8 |
| 58739.1684 | 17.50 | 306 | 12 | 58775.9458 | 4.50 | 166 | 10 |
| 58739.1927 | 5.00 | 153 | 7 | 58775.9458 | 5.50 | 114 | 9 |
| 58739.1927 | 7.00 | 139 | 6 | 58775.9458 | 6.50 | 147 | 9 |
| 58739.1927 | 4.50 | 142 | 10 | 58775.9458 | 7.50 | 118 | 8 |
| 58739.1927 | 5.50 | 138 | 9 | 58775.9677 | 8.50 | 142 | 8 |
| 58739.1927 | 6.50 | 129 | 9 | 58775.9677 | 9.50 | 121 | 8 |
| 58739.1927 | 7.50 | 144 | 8 | 58775.9677 | 10.50 | 146 | 8 |
| 58745.0560 | 2.75 | 194 | 16 | 58775.9677 | 11.50 | 162 | 9 |
| 58745.0560 | 3.25 | 254 | 12 | 58775.9934 | 12.50 | 143 | 9 |
| 58745.0569 | | | | | | | |

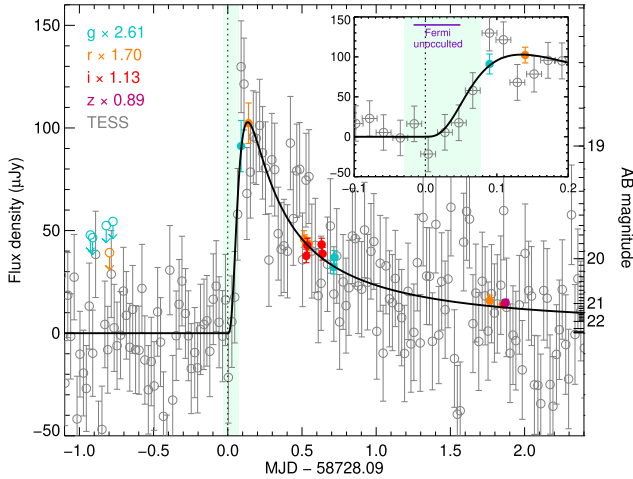


Figure 5. Early-time observations of AT 2019pim from *TESS*, P48, GIT, and LT. The black curve shows a broken power-law model fit to the *TESS* and ground-based data simultaneously; the flux scale for the ground-based filters has been shifted to align the data using this model. The shaded region shows a conservative bracketing of the potential explosion time, with the best-fit t_0 (for an assumed $\alpha_{\text{rise}} = 3.0$ and $s = 0.5$) indicated with a dotted vertical line. An inset focusing in on the region around the explosion time is shown at top right; the *Fermi*-GBM sensitivity window (Section 2.5) is indicated.

3.1 Explosion time and early decay

We fit an empirical model to all ground-based optical photometry within 4 d after discovery (plus all *TESS* data in the range MJD 58727.657–58729.158, or approximately -0.5 d to $+1.0$ d after the ZTF discovery observation). We initially assume a simple broken Beuermann et al. (1999) power law with the onset time and peak time being free parameters, although we later extend this to add a second additive power law and a jet break at later times (Section 3.2). The sharpness parameter was fixed at 0.5, and the power-law index of the rising phase of the afterglow is fixed to $\alpha_{\text{rise}} = +3.0$ (as expected for optical/X-ray emission from a relativistic constant velocity thin shell expanding into a uniform medium). The evolution of the afterglow is assumed to be achromatic but the relative flux in each band is a free parameter.

The resulting best-fitting curve is plotted in Figs. 5 and 6. The model indicates a peak close in time to the first ZTF detection and an explosion time ~ 2 h prior: for our assumed $\alpha_{\text{rise}} = +3.0$ and $s = 0.5$, we obtain an explosion time (MJD) of 58728.0898 ± 0.0289 (2σ) although this is strongly sensitive to those assumptions, and for a more sudden initial rise, the explosion time can be significantly more recent. The *TESS* measurement centred at MJD 58728.1573 is 2.6σ above the background, so we have reasonable confidence that the afterglow began to rise sometime within or before this exposure (i.e. no later than MJD 58728.168), placing a firm upper limit on the explosion time. A conservative bracketing of the exposure time combining these constraints is shown as the shaded region in Fig. 5 (MJD 58728.062–58727.168).

3.2 Late plateau and break

A single-component power-law fit to the light curve over the first five days suggests a post-peak decay index of $\alpha \approx -1$. However, the decay behaviour is clearly more complicated than this: between about 5 to 10 d, the rate of decay briefly becomes much shallower,

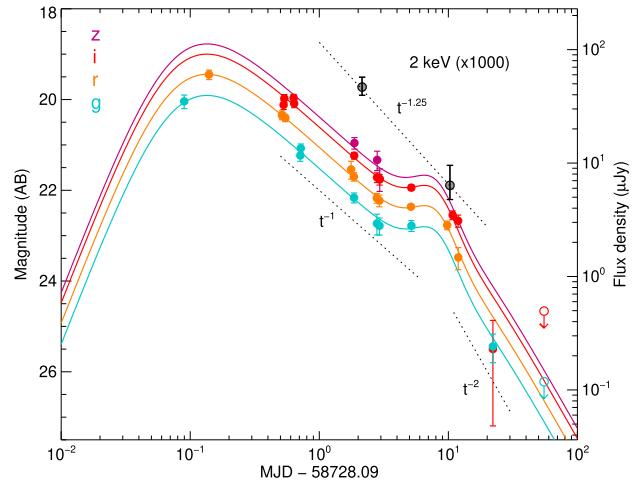


Figure 6. Complete ground-based optical light curve of AT 2019pim, on a logarithmic scale; the two XRT detections are also shown (rescaled by a factor of 10^3). The time axis is relative to the preferred explosion time of our model, although we emphasize that this is uncertain. The light curve exhibits an approximately t^{-1} decay before briefly leveling off, then rapidly steepening.

before then steepening dramatically, and there are no detections of the afterglow beyond 20 d even in deep Keck imaging.

To incorporate this behaviour, we introduced a second Beuermann et al. (1999) broken power-law component to the model described in Section 3.1 (which adds in flux space to the initial component; see e.g. equation 1 of Perley et al. 2008) as well as a late-time break at 20 d to an assumed final decay index of $\alpha_{\text{late}} = -2$. While this model is not unique (owing to the sparse nature of the post-plateau follow-up observations, it is not possible to robustly fit all parameters), it provides a good match to all the data and is used consistently to visualize the early-through-late-time optical light curve in subsequent figures.

3.3 Radio light curve

The radio light curve at a few select frequencies is shown in Fig. 7. It exhibits a gradual rise ($F \propto t^{+0.8}$ at high frequencies), peaks ~ 20 d post-discovery, and then fades ($t^{-1.3}$). Significant short-time-scale variability is superimposed on top of this slow evolution, especially at the lower frequencies (< 10 GHz) and early times ($t < 50$ d).

The rapid low-frequency variability results in complex radio spectra. Approximately coeval SEDs are shown in Fig. 8. Between 10–30 d the SEDs cannot be well fit with a power law (or broken power law) owing to modulations in the SED by a factor of ~ 1.5 – 2 , producing structure on a frequency scale of $\Delta\nu/\nu \approx 2$. This behaviour is present until at least 30 d, and may persist beyond that (although the more limited frequency coverage and lower S/N makes it difficult to be definitive). The average spectral index ($F_\nu \propto \nu^\beta$) (forcing a power-law fit to each spectrum for which multiple receivers were used, excluding measurements below 3 GHz) is typically about $\beta = +0.1$, although it ranges between -0.5 and $+0.6$.

This single-peaked light curve behaviour is typical of GRB afterglows, as the spectral break associated with the minimum synchrotron energy ν_m passes through the radio bands. It is difficult to clearly identify this break in any of the available radio spectra (shown in Fig. 8) as a result of what is likely quite strong interstellar scintillation (Section 5.1.3). However, the well-sampled multiband SEDs at $\Delta t \approx 11$ d and $\Delta t \approx 17$ d are broadly consistent with

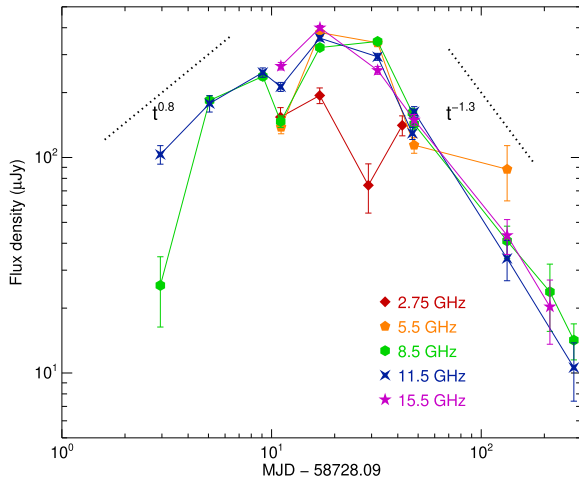


Figure 7. VLA radio light curve of AT2019pim at a few select frequencies. The high-frequency (>10 GHz) light curve shows relatively consistent behaviour, with a gradual rise followed by a decline. Lower frequencies exhibit strong interepoch variability out to late times, likely due to interstellar scintillation.

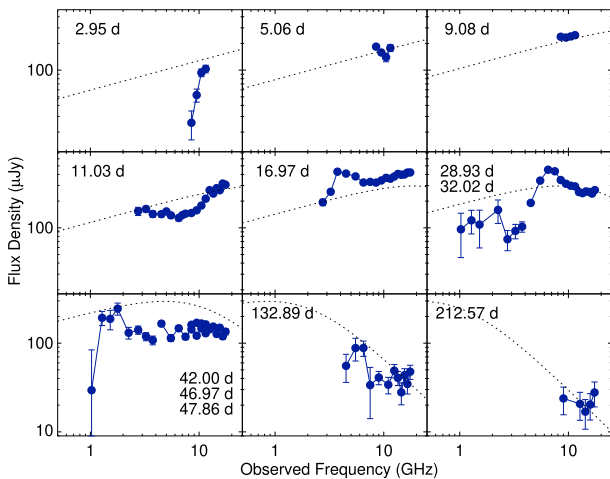


Figure 8. Radio SEDs of AT2019pim at different epochs (the observer-frame days elapsed since the preferred explosion time are indicated in each panel). In two cases, the low- and high-frequency blocks were observed on separate days. A simple model of the afterglow SED assuming standard ISM is shown. While the spectra broadly (within a factor of ~ 2) follow this model, the deviations over narrower bandwidths are significant, probably due to interstellar scintillation.

the $F_\nu \propto \nu^{+1/3}$ spectrum expected below the synchrotron peak (suggesting $\nu_m > 10$ GHz at this time), the $\Delta t \approx 45$ d spectrum is largely flat (suggesting $\nu_m \approx 10$ GHz), and the $\Delta t \approx 132$ d spectrum, while having low S/N, shows a negative spectral index (suggesting $\nu_m < 10$ GHz); this is broadly consistent with the expected passage of ν_m through the radio band for a relativistically expanding outflow. However, the strong scintillation and lack of low-frequency coverage during the D/C-configuration cycles do not allow us to robustly model the behaviour in more detail, or to easily discriminate between constant-density or r^{-2} density profiles. There is no obvious counterpart of the ‘bump’ and corresponding sharp dropoff seen in the optical light curve at 10 d, although the peak of the radio light curve occurs only a few days after this.

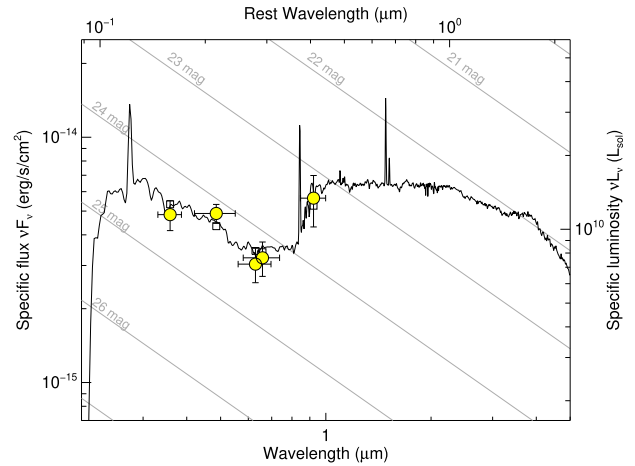


Figure 9. Population-synthesis fit to the host galaxy SED. Circles indicate host photometry; empty squares show synthetic photometry of the afterglow over these bands. Measurements are corrected for Galactic extinction. The best-fitting model is for a star-formation rate of $2.7 M_\odot \text{ yr}^{-1}$ and stellar mass of $M_* = 1.9 \times 10^{10} M_\odot$, typical of GRB host galaxies at these redshifts.

3.4 Optical SED and extinction column

The optical transient is quite red. We extracted the simultaneous *griz* SED of the transient using the LT data 1–3 d post-explosion and applied a GalKasliwal M. M. et al., 2019, PASKasliwal M. M. et al., 2019, PASPactic extinction correction ($E_{B-V} = 0.038$ mag; Schlafly & Finkbeiner 2011). A power-law fit to these data implies an apparent spectral index of $\beta = -1.70 \pm 0.14$ (using the convention $f_\nu \propto \nu^\beta$). The optical to X-ray spectral index at the same time is significantly shallower ($\beta_{OX} = -0.92$), implying that the optical flux is likely extinguished by moderate host-galaxy dust. The blue portion of the LRIS spectrum also shows slight curvature at approximately the expected location of the redshifted 2175 Å extinction feature commonly seen in local galaxies.

To constrain the extinction column, we assume an intrinsic optical spectral index of $\beta = -0.65$ (Section 5.2) and adopt a Fitzpatrick (1999) dust-extinction law (see also Fitzpatrick & Massa 1988, 1990; Cardelli, Clayton & Mathis 1989) with the values of most of the parameters set to their diffuse Milky Way values, with the exception that the strength of the 2175 Å bump is allowed to be a free parameter (c_3). We find a good fit to our spectrum for $E_{B-V} = 0.24$ mag and $c_3 = 1.0$ (red curve in Fig. 1), implying host extinction of about 1 mag in the observed optical bands.

3.5 Host-Galaxy SED

The late-time filter coverage is (marginally) sufficient to obtain basic constraints on the fundamental properties of the host galaxy using SED fitting. We use codes previously employed by Perley et al. (2014) and population-synthesis templates from Bruzual & Charlot (2003) to fit the *ugrRz* data against a model that assumes a single stellar population with a uniform star-formation history and Calzetti, Kinney & Storchi-Bergmann (1994) dust attenuation. The data are well fit by a model with a moderate star-formation rate ($\text{SFR} = 2.7^{+4.0}_{-1.1} M_\odot \text{ yr}^{-1}$), moderate stellar mass ($M_* = 1.9^{+0.5}_{-1.5} \times 10^{10} M_\odot$), and low to moderate dust extinction ($A_V = 0.18^{+0.36}_{-0.18}$ mag). These properties are typical of star-forming galaxies (and of long-GRB hosts) at similar redshifts. A plot of the SED is given in Fig. 9.

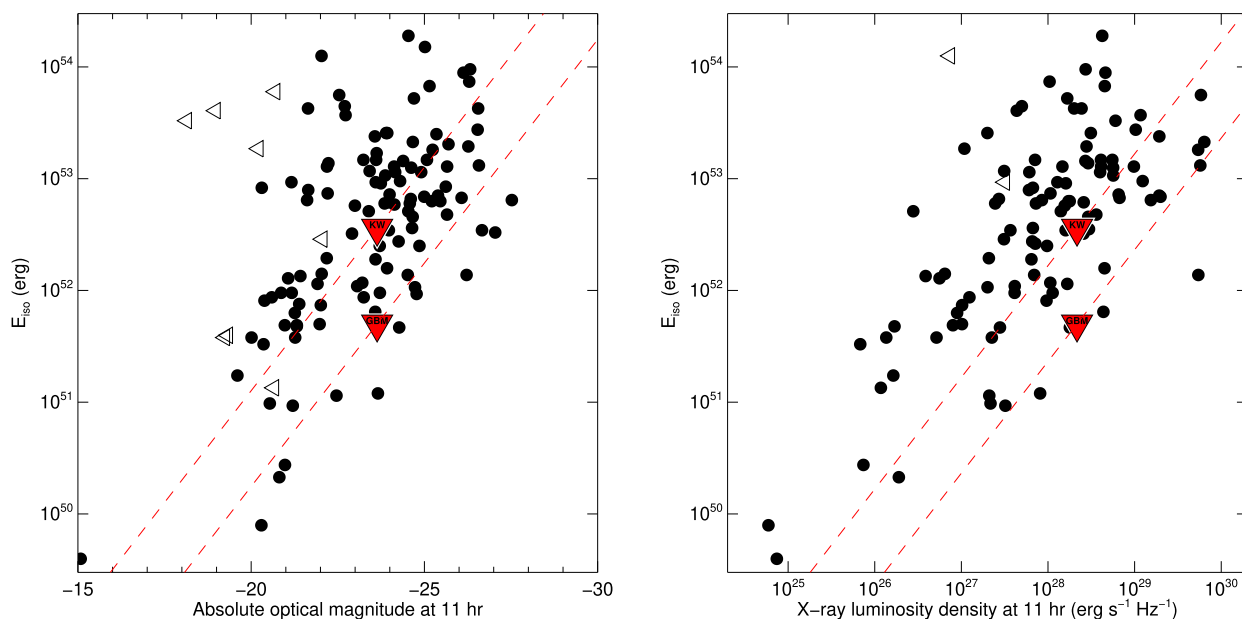


Figure 10. Afterglow luminosity versus 10–1000 keV prompt emission isotropic-equivalent energy for GRBs in the optical (left panel) and X-rays (right panel). Upper limits on the prompt emission for AT2019pim are shown as red triangles: the lower filled triangle is the GBM limit (for an event close in time to our best-fitting explosion time) and the upper triangle is the *Konus* limit (a more conservative limit allowing a burst during the GBM occultations). Most of the known GRB population for afterglows of comparable luminosities is ruled out by the GBM limit, although not by the *Konus* limit.

4 DISCUSSION

4.1 AT2019pim in context: empirical constraints on a GRB origin

As the first afterglow with both a confirmed redshift and strong limits on an associated gamma-ray counterpart, AT2019pim is of interest primarily as a candidate for a phenomenon related to but separate from ‘typical’ GRBs: a dirty fireball, an off-axis GRB, or a GRB with a smooth outflow free of internal shocks.

Before considering these possibilities, it should be emphasized that even the known GRB phenomenon (as selected by existing high-energy satellites) is extremely diverse: there are numerous examples of ‘normal’ but lower-luminosity GRBs¹⁸ which are visible in the low-redshift Universe yet would not be detectable to *Konus*, *Fermi*, or even *Swift* at higher redshifts (e.g. Singer et al. 2013; Schulze et al. 2014; Dichiara et al. 2022). Thus, as a first step, it is important to establish that AT2019pim stands out from the well-established GRB and afterglow population in at least some way.

We restrict our comparisons to long-duration GRBs specifically. While short GRBs may also produce afterglows, their optical luminosities are typically much lower, and even among the existing gamma-ray-selected population few or none would be detectable by ZTF at the distance of AT2019pim (Kann et al. 2011). Certain tidal disruption events also produce relativistic ‘afterglows’ (Bloom et al. 2011; Burrows et al. 2011; Levan et al. 2011; Zauderer et al. 2011; Andreoni et al. 2022), but these have quite distinctive X-ray and radio behaviour different from this event. The association of this event with a star-forming low-mass galaxy (Section 3.5) further supports this.

¹⁸We distinguish this population (with $E_{\text{iso}} = 10^{50}\text{--}10^{51}$ erg) from the truly low-luminosity GRBs such as GRB 980425 or GRB 060218 whose inferred energy outputs are orders of magnitude lower ($E_{\text{iso}} = 10^{48}\text{--}10^{50}$ erg) and which could in principle be a separate population (Liang et al. 2007; Virgili, Liang & Zhang 2009; Bromberg, Nakar & Piran 2011; Nakar 2015).

Fig. 10 shows the afterglow luminosity at the commonly standardised time of 11 h post-GRB (observed) versus the prompt emission $E_{\text{iso},\gamma}$ for a sample of pre-*Swift* and early-*Swift* bursts (from Nysewander, Fruchter & Pe’er 2009). GRB fluences were converted from the 15–150 keV band to the 10–1000 keV band using an average correction factor of 2.39, derived from our preferred spectral model. Afterglow luminosities are calculated assuming a basic *K*-correction factor of $1+z$. Luminosities could be further corrected to standard times and frequencies in the rest frame as $F_{\text{rest}} = F_{\text{obs}}(1+z)^\alpha/(1+z)^\beta$, assuming a GRB light curve power-law index of α and spectral index of β ; for typical afterglows at these frequencies and time-scales $\alpha \approx \beta (\approx -1)$, these factors helpfully cancel out, and we neglect this correction. Under these assumptions, the left plot can be treated as an *R*-band absolute magnitude at 11 rest-frame hours or equivalently as a 3000 Å absolute magnitude at 5 rest-frame hours; the right plot can be treated as a 1 keV rest-frame luminosity density at 11 rest-frame hours or a 2.2 keV rest-frame luminosity density at 5 rest-frame hours.

The GBM limit on GRB emission from AT2019pim is shown as the lower of the two solid red triangles in each panel of Fig. 10. The X-ray flux is extrapolated backward to 11 hr assuming $\alpha = -1$. The bulk of known GRBs with comparable afterglow luminosities have prompt emission substantially brighter (by a factor of 10–30) than what the *Fermi* limit allows for AT2019pim. Thus, assuming that the explosion did indeed occur at or close to our inferred explosion time, this event is clearly uncharacteristic of the ‘normal’ GRB population (if not completely unprecedented: a handful of GRBs with lower E_{iso} values do have comparable afterglows).

The GBM limit covers the most probable time of explosion but (due to occultations) does not cover the entire allowed explosion time window. The shallower limit from *Konus* is also shown as the upper triangle in Fig. 10. This also rules out most GRBs of comparable afterglow luminosity, but a substantial fraction of the population does lie below the *Konus* limit, and so we cannot fully rule out a GRB scenario from high-energy limits alone. However, the early

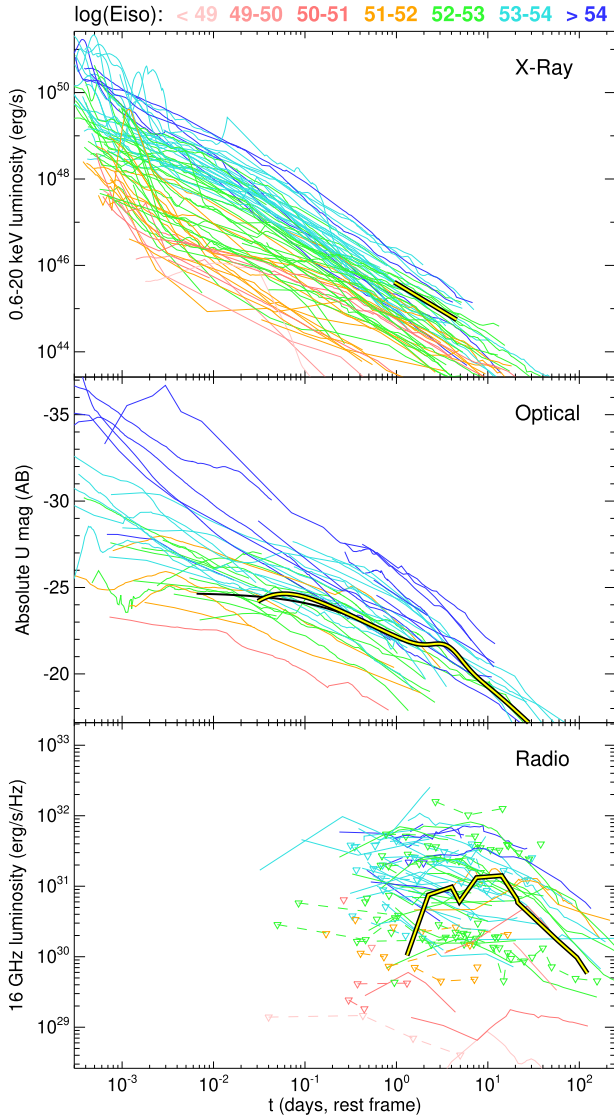


Figure 11. Comparison between the X-ray, optical, and radio light curves of AT 2019pim (thick yellow/black line) and GRB afterglows (colour-coded by E_{iso}). In the optical panel, the yellow/black curve represents our empirical model, starting from the time of the first *TESS* detection; the solid-black line indicates an alternative fit with the explosion time t_0 set to the end of our bracketed window. The afterglow is similar in luminosity (in X-ray, optical, and radio bands) to GRB afterglows with $E_{\text{iso}} \approx 10^{52}\text{--}10^{53}$ erg.

light curve would be unusual for a GRB occurring during either of the occultations: a GRB in the first occultation would have an unusually long rise time of almost 3 h; a GRB in the second occultation would have to exhibit a fast rise time and then a multihour plateau with virtually no fading.

We can also perform comparisons of this type more qualitatively over the entire light curve to compare the general behaviour and time-dependent luminosity to the general afterglow population. Fig. 11 shows the X-ray, optical, and radio light curves of this event in comparison to GRBs, colour-coded by E_{iso} . The comparison population is the same as in the equivalent figure of Perley et al. (2014): specifically, events from the sample analyses of Evans et al. (2007), Cenko et al. (2009), Kann et al. (2011), and Chandra & Frail (2012). The luminosity and general decay rate of AT 2019pim are

fairly typical at *late* times, although at every wavelength the luminosity is characteristic only of high- E_{iso} ($10^{52} - 10^{54}$ erg) events, as expected given Fig. 10. Comparing the early phase is more difficult owing to the uncertain explosion time of AT 2019pim, but rise times as slow as 0.5 rest-frame hours are rare, constituting no more than a few per cent of known afterglows with early-time follow-up observations (although a few examples do exist, e.g. Margutti et al. 2010). This has also been noted in other early-afterglow samples (Rykoff et al. 2009; Hascoët et al. 2014; Melandri et al. 2014a; Ghirlanda et al. 2018; Page et al. 2019; Jayaraman et al. 2023).

5 PHYSICAL CONSTRAINTS ON THE OUTFLOW

5.1 Constraints from basic physical arguments

Even in the absence of a complete model to explain the multiwavelength behaviour of the afterglow across all bands, the observations can be used directly to constrain the source size and therefore outflow velocity. Three independent constraints are possible: a lower limit from the emergence (rise) time of the afterglow, a lower limit from the non-thermal spectrum, and an upper limit based on the presence of strong scintillation at late times.

5.1.1 Constraint from rise time of afterglow

The afterglow forward shock reaches peak luminosity when the ejecta have had time to sweep up sufficient material from the surrounding medium to gain mass energy approximately comparable to that of the initial outflow (for a review, see e.g. Mészáros 2006). Time-of-flight effects greatly compress this characteristic time-scale for material moving towards the observer at relativistic speeds, making the early afterglow a particularly sensitive probe of the Lorentz factor. In the case of a uniform and wind-driven medium, respectively, the equations relating the observed deceleration time t to the maximum Lorentz factor Γ are

$$\Gamma = k_0 \left(\frac{E_K}{nm_\rho c^5} \right)^{1/8} \left(\frac{t}{1+z} \right)^{-3/8},$$

$$\Gamma = k_2 \left(\frac{E_K}{Am_\rho c^3} \right)^{1/4} \left(\frac{t}{1+z} \right)^{-1/4}.$$

Here, E_K is the isotropic-equivalent energy of the outflow, n is the density of the circumburst interstellar medium (ISM), and A is the wind density parameter ($\rho = Ar^{-2}$). The numerical prefactors k_0 and k_2 have values of order unity but vary slightly according to different authors (we adopt $k_0 = 0.65$ and $k_2 = 0.45$, following Sari & Piran 1999; see Ghirlanda et al. 2018 for a compilation of alternative values).

The *TESS* observations strongly suggest an afterglow rise time of 1–4 h (observer frame). If this rise is the result of deceleration of the afterglow, the corresponding fiducial ranges of the Lorentz factor in the uniform and wind cases, respectively, are

$$28 \lesssim \frac{\Gamma}{(E_{53}/n_0)^{1/8}} \lesssim 47,$$

$$9 \lesssim \frac{\Gamma}{(E_{53}/A^*)^{1/4}} \lesssim 14.$$

Here, $E_{53} = E_K/(10^{53} \text{ erg})$, $n_0 = n/\text{cm}^{-3}$, and $A^* = A/(3 \times 10^{35} \text{ g cm}^{-1})$. The lower limits are set by a $t \lesssim 4$ h deceleration time, and the upper limits by a $t \gtrsim 1$ h deceleration time.

It is important to note that a peak in the light curve can occur earlier or later than the deceleration time owing to other effects. An

earlier peak can be produced by internal-shock processes (flaring), while a later peak can occur due to late-time energy reinjection from the central engine into the external shock or to the passage of peak synchrotron frequency ν_m through the optical band. The former case would void the lower limit, while the latter case would void the upper limit. The smooth nature of the *TESS* light curve suggests that the lower limit is probably robust, but the upper limit can certainly be called into question: our modelling (Section 5.2) does indeed suggest that ν_m is likely to be close to the optical band at 1–4 h.

5.1.2 Lower limit from non-thermal spectrum

Compact radio sources exhibit steep radio spectra (ν^2 to $\nu^{5/2}$) on account of synchrotron self-absorption of radio emission from within the dense shocked gas. Our first radio observation, at $t = 2.86$ d, may be self-absorbed: it falls below the projected synchrotron spectrum and exhibits a steep downturn toward lower frequencies. As strong scintillation was occurring at this time and only *X*-band observations are available, it is not possible to confirm this. However, by the time of the first multireceiver observation at $t = 11$ d, the radio spectrum is clearly not self-absorbed, indicating that it has expanded sufficiently to be optically thin above $\nu > 3$ GHz. Using equation 5 from Barniol Duran, Nakar & Piran (2013) and assuming $\nu_m \approx 50$ GHz, $\nu_a \leq \nu_m$, and a full filling factor, we estimate a minimum average Lorentz factor of $\Gamma_{\text{av},10\text{d}} > 2.7$ (at 10 d).

This is only an average limit out to late times. However, the jet velocity is not constant during this phase: the Lorentz factor drops with time as $\Gamma \propto t^{-3/8}$ in a constant-density medium, or as $\Gamma \propto t^{-1/4}$ in a wind medium. Extrapolating back to the upper limit on the peak time of the afterglow at ~ 4 h, we infer $\Gamma_{\text{av},4\text{hr}} \gtrsim 13$ (uniform) or $\Gamma_{\text{av},4\text{hr}} \gtrsim 8$ (wind).

If the first radio epoch was in fact self-absorbed, the equivalent maximum average Lorentz factor extrapolated to 4 h is $\Gamma_{\text{av},4\text{hr}} \lesssim 11$ in the uniform case, or $\Gamma_{\text{av},4\text{hr}} \lesssim 8$ in the wind case. As this is in tension with the more secure estimate from the 11 d spectrum, this suggests that the first epoch was probably not self-absorbed. (Indeed, a change from self-absorbed to unabsorbed on these time-scales would be inconsistent with an afterglow expanding into a constant-density ISM to begin with, as ν_a is constant within the model.)

5.1.3 Upper limit from interstellar scintillation

The radio spectrum (Fig. 8) shows wiggles in frequency space and short-time-scale fluctuations (by a factor of ~ 2) until at least 30 d, and probably as late as 130 d. This strongly suggests that the source is small enough in angular size until at least 30 d to be affected by strong interstellar scintillation (ISS) from electrons along the line of sight through our Galaxy. From fig 1 to 2 of Walker (2001) (Erratum to Walker 1998), the critical frequency for ISS in this direction is $\nu_0 \approx 12$ GHz and the Fresnel scale at this frequency is $\theta_{F0} \approx 2.5$ μ arcsec; the latter corresponds to a physical scale of 6.5×10^{16} cm (25 light-days) given the angular diameter distance of the source. Large-amplitude ISS (modulation index ~ 1) near ν_0 requires a source size comparable to the Fresnel scale, so the implied $\Gamma_{\text{av},30\text{d}}$ is $\Gamma \leq 2$.

To convert this limit on the average Lorentz factor to a limit on the post-deceleration Lorentz factor, we use the same general reasoning as in Section 5.1.2 and extrapolate back our late-time limit to the peak time of the afterglow. However, as our modelling (Section 5.2) indicates that a jet break likely took place at 10–20 d, we must consider the post-jet evolution. Conservatively adopting the earliest

possible jet-break time of $t_j = 10$ d, we first extrapolate the 30 d size constraint to the jet-break time assuming $\theta \propto t^{1/4}$ (the angular size evolution after the jet break; Granot, Ramirez-Ruiz & Loeb 2005) to obtain $\theta_{10\text{d}} < 1.9$ μ as. We further extrapolate the size evolution from the jet break time to the peak time according to $\theta \propto t^{5/8}$ (ISM) or $\theta \propto t^{3/4}$ (wind). Finally, we estimate the minimum average Lorentz factor $\Gamma = R/(c t_{\text{rest}}) = \theta D_{\text{ang}}(1+z)/(c t_{\text{obs}})$. Conservatively adopting 1 h as the time of peak, we infer an Lorentz factor upper limit of $\Gamma_{\text{av},1\text{h}} < 33$ (uniform) or $\Gamma_{\text{av},1\text{h}} < 17$ (wind).

As was the case with the deceleration constraint itself, this limit can be treated as a limit on the true initial Lorentz factor only if the optical peak is due to deceleration. If the observed peak originates from a different mechanism (e.g. ν_m break), then deceleration occurred earlier and the initial Lorentz factor can be higher. Additionally, caution is warranted in interpreting constraints based on scintillation arguments, since many of the best-observed GRB afterglows in the literature do not conform well to the predictions of scintillation theory (Alexander et al. 2019; Marongiu et al. 2022).

Taken together, the three lines of argument above suggest that the bulk of the material along our line of sight was at least moderately relativistic ($\Gamma > 10$), but need not have been highly relativistic ($\Gamma > 50$).

5.2 Constraints from afterglow modelling

Additionally, we modeled the entire afterglow data set using a numerical code based on the method presented by Lamb, Mandel & Resmi (2018). Free parameters in the model include the initial Lorentz factor Γ_0 , jet half-opening angle θ_j , viewing angle ι , as well as the (isotropic-equivalent) kinetic energy E_K , the circumburst density n , and the time of explosion t_0 (measured relative to MJD 58728.09). This model also permits a variety of jet-structure profiles and allows for the possibility of late-time energy injection (‘refreshed’ shocks; see Lamb, Levan & Tanvir 2020, for details). We attempted three types of model: a simple uniform (‘top-hat’) jet with no energy injection, a uniform jet with energy injection, and a structured jet without energy injection. In each case we fix the microphysical parameters $\epsilon_B = 0.001$, $\epsilon_e = 0.1$, $\epsilon_N = 0.15$, and $p = 2.3$ (the fraction of energy given to the magnetic fields, the accelerated electrons, the fraction of accelerated electrons that contribute to synchrotron emission, and the power-law index for the relativistic electron distribution, respectively). These values were chosen following preliminary exploration of the theoretical parameter space via nested sampling with priors informed by precedent from fitting previous GRBs, as they were able to reproduce the salient features of the data across a variety of models.

Consistent with our analysis using basic physical arguments, most models converge toward Lorentz factors that are lower than typical for GRBs but still relativistic ($\Gamma = 30$ –50). In the case of a structured jet, higher core Lorentz factors are preferred, but the viewing angle is at the edge of the jet core and the material ejected toward the viewer, consistent with a scenario in which the most relativistic material is beamed outside the line of sight.

To contrast various potential interpretations of the afterglow, we focus on five specific cases below:

(i) Model G (‘high- Γ ’): A uniform, on-axis jet with a ‘high’ Lorentz factor ($\Gamma \approx 100$). This model is generally expected to produce observable gamma-rays, though an underluminous/soft burst may be possible if the outflow is very smooth (Barraud et al. 2005; Zitouni et al. 2008).

(ii) Model A (‘mid- Γ ’): A uniform, on-axis jet with a ‘moderate’ Lorentz factor ($\Gamma \approx 55$), close to the threshold where high-energy

Table 5. Model parameters.

| Parameter | | G high- Γ | A mid- Γ | B low- Γ | C off-axis | D refreshed |
|---------------------------|----------------------|---------------------|--------------------|--------------------|---------------|----------------|
| Γ_0 [Γ_c] | | 100 | 55 | 35 | 130 | 45 [7] |
| E_K [f_e] | (10^{53} erg) | 3.5 | 2 | 2 | 6 | 1.6 [6.4] |
| n | (cm^{-3}) | 0.5 | 2 | 3 | 2.5 | 2.5 |
| θ_j [θ_e] | (rad) | 0.22 | 0.22 | 0.22 | 0.09 [0.4] | 0.15 |
| θ_i | (rad) | 0 | 0 | 0 | 0.13 | 0 |
| t_0 | (d) | 0.01 | 0 | -0.02 | -0.01 | -0.02 |

emission should be suppressed given typical inferred emission region sizes from previous luminous GRBs (see, e.g. Lamb & Kobayashi 2016; Matsumoto, Nakar & Piran 2019).

(iii) Model B (‘low- Γ ’): A uniform, on-axis jet with a ‘low’ Lorentz factor ($\Gamma \approx 35$), for which pair production should almost completely suppress high-energy photons.

(iv) Model C (‘grazing’): A structured relativistic jet with a ‘high’ Lorentz factor core, but viewed from just outside this core.

(v) Model D (‘refreshed’): A uniform, on-axis, jet with a low to moderate Lorentz factor and late-time energy injection.

Model parameters in each case were chosen from regions of the posterior distribution of the model runs that indicate reasonably good fits to the data (at least in comparison to other models); values are given in Table 5. In the case of model C, E_K is the isotropic-equivalent energy along the symmetry axis, and θ_j refers to the jet structure core angle. We assume a Gaussian jet profile¹⁹ where the energy and the Lorentz factor vary with lateral angle as $E(\theta \leq \theta_e) = E_K e^{-0.5(\theta/\theta_e)^2}$, and $\Gamma(\theta) = 1 + (\Gamma_0 - 1) e^{-0.5(\theta/\theta_e)^2}$ for $\theta < \theta_e$ and $E(\theta > \theta_e) = 0$. In the case of model D, the Lorentz factor of the decelerating blast wave when energy injection begins is given by Γ_c and the fractional energy increase originating from the refreshed shock is parametrized as f_e .

The model light curves are plotted against the data in Fig. 12. The g and r optical bands have been shifted to match the i band, as have the TESS data.

It can be seen that all of these models reproduce the basic observations (the approximate peak times, decay slopes, and relative fluxes in each band), although none of them fully reproduce the optical flattening or the much steeper evolution in the optical compared to the radio at late times. Model D (‘refreshed’) comes closest to reproducing the late-time evolution (this model was introduced for this reason), though it does not fully explain the optical bump feature and it overpredicts the radio data around peak brightness. Model A (mid- Γ) underpredicts both the late-time optical and radio data but better explains the rise time-scale. Model G (high- Γ) is similar but also greatly overpredicts the X-rays.

We cannot formally rule out any of the scenarios on the basis of the afterglow alone, both owing to the simplified nature of the models and because we have not yet performed an exhaustive search of the parameter space for each case. However, the modelling establishes that a low- Γ outflow is indeed consistent with most of the key features in the data (rise time, decay rate, and multiwavelength spectrum). On the other hand, while a high- Γ on-axis outflow is not a good match

¹⁹Our choice of a Gaussian for this model is ad-hoc, and some studies have preferred other forms of the dependence of the energy on lateral angle, in particular a power law: (Beniamini, Gill & Granot 2022; Gill & Granot 2023; O’Connor et al. 2023). However, the effect of the details of the jet structure on the light curve after peak is limited, and similar conclusions would have been obtained for an alternative structure model.

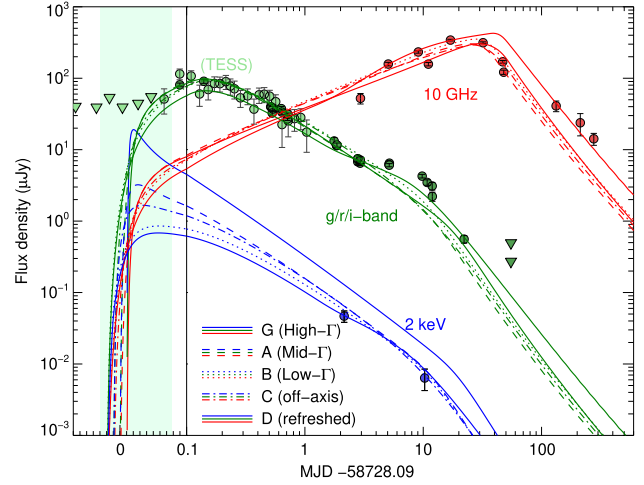


Figure 12. Afterglow models fit to the X-ray, optical, and radio light curves of AT 2019pim. The five models are described in the text. All of the models reproduce the basic qualitative behaviour at each wavelength, although none can reproduce the features in detail. The axis scale is logarithmic in time in the right segment of the plot and linear in the left segment; the observed g and i bands have been shifted to match the r band.

to the data, a classical GRB is fully consistent with the observations if the jet was observed slightly off-axis.

6 CONCLUSIONS

While AT 2019pim is unambiguously the afterglow of a relativistic explosion, its rise time to peak is substantially slower than is typical of afterglows of known gamma-ray bursts, and non-detections by GBM and Konus rule out prompt gamma-ray emission at a limit comparable to the fluence expected for GRB afterglows of comparable luminosity. These properties are consistent with, although do not strictly require, a model in which the early afterglow radiation that is observed is produced by ejecta moving toward us at a moderate initial Lorentz factor ($\Gamma \approx 10$ –50). This is substantially less than what has been reported for any classical (i.e. non-low-luminosity) GRB to date (Hascoët et al. 2014; Chen, Liu & Wang 2018; Ghirlanda et al. 2018, although c.f. Dereli-Bégué et al. 2022.)

Our data are not able to distinguish between models under which the low- Γ material originates from an on-axis jet with an intrinsically low initial Lorentz factor (a ‘dirty fireball’), versus low- Γ material from the high-latitude component of a structured jet seen partially off-axis (such that only the material along our line of sight is low- Γ , and a classical GRB was produced in some other direction). Additionally, while our modelling does not prefer a high- Γ on-axis scenario, we cannot strictly rule out a scenario in which AT2019pim is the afterglow of a GRB with low gamma-ray efficiency, particularly if it occurred during one of the *Fermi* occultations.

Additional intensive studies of future ‘orphan’ afterglow events will be needed to securely identify whether dirty fireballs truly exist in nature (or to rule them out if they do not), and to study the structure of the jet in classical GRBs. Fortunately, AT 2019pim was only the first example of a well-observed optically selected afterglow of this nature. Since the discovery of AT 2019pim, ZTF has already increased the size of the orphan afterglow sample by an order of magnitude, including the discovery of AT 2021lfa, which also shows compelling evidence of an extended (~ 3 h) rise time characteristic of a dirty fireball (Lipunov et al. 2022), and the recent detection of an afterglow with even more constraining limits on

accompanying gamma-ray emission (Li et al. 2024). Particularly notable is the detection of AT2022cmc, a relativistic transient with an inferred Lorentz factor of only $\Gamma \approx 10$ (Andreoni et al. 2022; Pasham et al. 2023; Rhodes et al. 2023, cf. Yao et al. 2023): while its origin appears to be due to a tidal disruption of a star rather than a collapse, it clearly demonstrates that optical surveys are quite sensitive to energetic relativistic transients across the entire range of potential Lorentz factors. While the assemblage of optically selected afterglows remains too small at the present time to draw firm conclusions on the nature of the population, the techniques to find events of this nature are now well established and should lead to more discoveries in the coming years.

Continued improvements to afterglow search methods in large surveys and the commissioning or expansion of additional wide-field facilities capable of high-cadence monitoring over large areas (such as GOTO and ATLAS) should increase the discovery rate in the coming years, and even more powerful surveys such as the upcoming Large Array Survey Telescope (Ofek et al. 2023) and proposed Argus Array (Law et al. 2022) will further extend these capabilities. Additionally, upcoming powerful radio facilities such as the Next-Generation VLA (ngVLA; Murphy 2018) and Square Kilometre Array (SKA) will enable late-time calorimetry and possibly direct imaging of the jet, permitting distinguishing off-axis from on-axis cases. Soft X-ray surveys (including the recently launched Einstein Probe, and proposed future facilities such as THESEUS or HiZ-GUNDAM; Yonetoku et al. 2014; Amati et al. 2021; Ghirlanda et al. 2021) also represent a promising means of low- Γ afterglow discovery. Comprehensive observational studies of individual events gathered by each of these surveys, together with comparative studies of afterglow populations selected at different wavelengths and different time-scales, will allow us to finally produce a complete picture of energetic, relativistic ejection from collapsing stars.

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DATA AVAILABILITY

All flux density measurements of the afterglow underlying this article are available in the article and in its online supplementary material. Additionally, the original raw data from LT, Keck, TESS, and VLA are available in public archives hosted by their respective facilities.

REFERENCES

- Abbott B. P. et al., 2018, *Living Rev. Relativ.*, 21, 3
 Abbott R. et al., 2021, *Phys. Rev. X*, 11, 021053
 Acernese F. et al., 2015, *Class. Quantum Gravity*, 32, 024001
 Alard C., 2000, *A&AS*, 144, 363
 Alard C., Lupton R. H., 1998, *ApJ*, 503, 325
 Alexander K. D. et al., 2019, *ApJ*, 870, 67
 Amati L., 2006, *MNRAS*, 372, 233
 Amati L., Della Valle M., Frontera F., Malesani D., Guidorzi C., Montanari E., Pian E., 2007, *A&A*, 463, 913
 Amati L. et al., 2021, *Exp. Astron.*, 52, 183
 Andreoni I. et al., 2020, *MNRAS*, 491, 5852
 Andreoni I. et al., 2021, *ApJ*, 918, 63
 Andreoni I. et al., 2022, *Nature*, 612, 430
 Band D. L., 2003, *ApJ*, 588, 945
 Barniol Duran R., Nakar E., Piran T., 2013, *ApJ*, 772, 78
 Barraud C., Daigne F., Mochkovitch R., Atteia J. L., 2005, *A&A*, 440, 809
 Barthelmy S. D. et al., 2005, *Space Sci. Rev.*, 120, 143
 Bauer F. E. et al., 2017, *MNRAS*, 467, 4841
 Bellm E. C. et al., 2019a, *PASP*, 131, 018002
 Bellm E. C. et al., 2019b, *PASP*, 131, 068003
 Beniamini P., Duque R., Daigne F., Mochkovitch R., 2020, *MNRAS*, 492, 2847
 Beniamini P., Gill R., Granot J., 2022, *MNRAS*, 515, 555
 Berger E. et al., 2013, *ApJ*, 779, 18
 Beuermann K. et al., 1999, *A&A*, 352, L26
 Bhalerao V. et al., 2017, *ApJ*, 845, 152
 Bloom J. S. et al., 2011, *Science*, 333, 203
 Bromberg O., Nakar E., Piran T., 2011, *ApJ*, 739, L55
 Bruzual G., Charlot S., 2003, *MNRAS*, 344, 1000
 Burrows D. N. et al., 2005, *Space Sci. Rev.*, 120, 165
 Burrows D. N. et al., 2011, *Nature*, 476, 421
 Calzetti D., Kinney A. L., Storchi-Bergmann T., 1994, *ApJ*, 429, 582
 Cano Z., 2014, *ApJ*, 794, 121
 Cano Z., Wang S.-Q., Dai Z.-G., Wu X.-F., 2017, *Adv. Astron.*, 2017, 8929054
 Cardelli J. A., Clayton G. C., Mathis J. S., 1989, *ApJ*, 345, 245
 Cenko S. B. et al., 2009, *ApJ*, 693, 1484
 Cenko S. B. et al., 2010, *ApJ*, 711, 641
 Cenko S. B. et al., 2011, *ApJ*, 732, 29
 Cenko S. B. et al., 2013, *ApJ*, 769, 130
 Cenko S. B. et al., 2015, *ApJ*, 803, L24
 Chandra P., Frail D. A., 2012, *ApJ*, 746, 156
 Chen Y., Liu R.-Y., Wang X.-Y., 2018, *MNRAS*, 478, 749
 Christensen L. et al., 2017, *A&A*, 608, A84
 Churchill C. W., Evans J. L., Stemmock B., Nielsen N. M., Kacprzak G. G., Murphy M. T., 2020, *ApJ*, 904, 28
 Corsi A. et al., 2017, *ApJ*, 847, 54
 Dai Z. G., Gou L. J., 2001, *ApJ*, 552, 72
 Dekany R. et al., 2020, *PASP*, 132, 038001
 Della Valle M. et al., 2006, *Nature*, 444, 1050
 Dereli-Bégué H., Pe'er A., Ryde F., Oates S. R., Zhang B., Dainotti M. G., 2022, *Nat. Commun.*, 13, 5611
 Dermer C. D., Chiang J., Mitman K. E., 2000, *ApJ*, 537, 785
 Dichiaro S. et al., 2022, *MNRAS*, 512, 2337
 Evans P. A. et al., 2007, *A&A*, 469, 379
 Evans P. A. et al., 2009, *MNRAS*, 397, 1177
 Fausnaugh M. M. et al., 2021, *ApJ*, 908, 51
 Fausnaugh M. M. et al., 2023, *ApJ*, 956, 108
 Fitzpatrick E. L., 1999, *PASP*, 111, 63
 Fitzpatrick E. L., Massa D., 1988, *ApJ*, 328, 734
 Fitzpatrick E. L., Massa D., 1990, *ApJS*, 72, 163
 Fremling C., 2019, Transient Name Server Discovery Report, 2019-1722
 Fynbo J. P. U. et al., 2006, *Nature*, 444, 1047
 Gal-Yam A. et al., 2006, *Nature*, 444, 1053
 Gehrels N., Mészáros P., 2012, *Science*, 337, 932
 Gehrels N. et al., 2004, *ApJ*, 611, 1005
 Gehrels N. et al., 2006, *Nature*, 444, 1044
 Gendre B. et al., 2013, *ApJ*, 766, 30
 Ghirlanda G. et al., 2018, *A&A*, 609, A112
 Ghirlanda G. et al., 2021, *Exp. Astron.*, 52, 277
 Gill R., Granot J., 2023, *MNRAS*, 524, L78
 Goldstein A., Connaughton V., Briggs M. S., Burns E., 2016, *ApJ*, 818, 18
 Graham M. J. et al., 2019, *PASP*, 131, 078001
 Granot J., Kumar P., 2003, *ApJ*, 591, 1086
 Granot J., Panaitescu A., Kumar P., Woosley S. E., 2002, *ApJ*, 570, L61
 Granot J., Ramirez-Ruiz E., Loeb A., 2005, *ApJ*, 618, 413
 Greiner J. et al., 2015, *Nature*, 523, 189
 Gruber D. et al., 2014, *ApJS*, 211, 12
 Hascœt R., Beloborodov A. M., Daigne F., Mochkovitch R., 2014, *ApJ*, 782, 5
 Hjorth J., Bloom J. S., 2012, in Kouveliotou C., Wijers R. A. M. J., Woosley S., eds, *The Gamma-Ray Burst—Supernova Connection*. Cambridge Univ. Press, Cambridge, p. 169
 Ho A. Y. Q. et al., 2018, *ApJ*, 854, L13
 Ho A. Y. Q., Cenko S. B., Perley D. A., 2019, *GRB Coord. Netw. Circ.*, 25658
 Ho A. Y. Q. et al., 2020, *ApJ*, 905, 98
 Ho A. Y. Q. et al., 2022, *ApJ*, 938, 85
 Huang Y. F., Dai Z. G., Lu T., 2002, *MNRAS*, 332, 735
 Jayaraman R., Fausnaugh M., Ricker G. R., Vanderspek R., Mo G., 2024, *ApJ*, 972, 162
 Jin Z.-P., Li X., Cano Z., Covino S., Fan Y.-Z., Wei D.-M., 2015, *ApJ*, 811, L22
 Kann D. A. et al., 2011, *ApJ*, 734, 96
 Kasliwal M. M. et al., 2019, *PASP*, 131, 038003
 Kool E. et al., 2019, *GRB Coord. Netw. Circ.*, 25616
 Kouveliotou C., Meegan C. A., Fishman G. J., Bhat N. P., Briggs M. S., Koshut T. M., Paciesas W. S., Pendleton G. N., 1993, *ApJ*, 413, L101
 Kulkarni S. R., Rau A., 2006, *ApJ*, 644, L63
 Kulkarni S. R. et al., 1998, *Nature*, 395, 663
 Kumar H. et al., 2022, *AJ*, 164, 90
 LIGO Scientific Collaboration and Virgo Collaboration, 2019, *GRB Coord. Netw. Circ.*, 25606
 Lamb G. P., Kobayashi S., 2016, *ApJ*, 829, 112
 Lamb D. Q., Donaghy T. Q., Graziani C., 2005, *ApJ*, 620, 355
 Lamb G. P., Mandel I., Resmi L., 2018, *MNRAS*, 481, 2581
 Lamb G. P., Levan A. J., Tanvir N. R., 2020, *ApJ*, 899, 105
 Law C. J., Gaensler B. M., Metzger B. D., Ofek E. O., Sironi L., 2018, *ApJ*, 866, L22
 Law N. M. et al., 2022, *PASP*, 134, 035003
 Levan A. J. et al., 2011, *Science*, 333, 199
 von Kienlin A. et al., 2014, *ApJS*, 211, 13
 Levan A. J. et al., 2014, *ApJ*, 781, 13
 Levan A. et al., 2023, *Nature*, 626, 737

- Li M. L. et al., 2024, *ApJ*, preprint (arXiv:2411.07973)
- Liang E., Zhang B., Virgili F., Dai Z. G., 2007, *ApJ*, 662, 1111
- Lipunov V. M., Postnov K. A., Prokhorov M. E., 2001, *Astron. Rep.*, 45, 236
- Lipunov V. M. et al., 2022, *Astron. Lett.*, 48, 623
- Margutti R. et al., 2010, *MNRAS*, 402, 46
- Margutti R. et al., 2014, *ApJ*, 797, 107
- Marongiu M., Guidorzi C., Margutti R., Coppejans D. L., Martone R., Kamble A., 2019, *ApJ*, 879, 89
- Marongiu M. et al., 2022, *A&A*, 658, A11
- Masci F. J. et al., 2019, *PASP*, 131, 018003
- Matsumoto T., Nakar E., Piran T., 2019, *MNRAS*, 486, 1563
- Meegan C. et al., 2009, *ApJ*, 702, 791
- Melandri A. et al., 2014a, *A&A*, 565, A72
- Melandri A. et al., 2014b, *A&A*, 567, A29
- Melandri A. et al., 2019, *A&A*, 621, A81
- Mészáros P., 2006, *Rep. Prog. Phys.*, 69, 2259
- Mészáros P., Rees M. J., Wijers R. A. M. J., 1998, *ApJ*, 499, 301
- Murphy E. J., 2018, in Tarchi A., Reid M. J., Castangia P., eds, Proc. IAU Symp. 336, *Astrophysical Masers: Unlocking the Mysteries of the Universe*. Cambridge Univ. Press, Cambridge, p. 426
- Murphy E. J. et al., 2011, *ApJ*, 737, 67
- Nakar E., 2015, *ApJ*, 807, 172
- Nakar E., Piran T., Granot J., 2002, *ApJ*, 579, 699
- Narayana Bhat P. et al., 2016, *ApJS*, 223, 28
- Nysewander M., Fruchter A. S., Pe'er A., 2009, *ApJ*, 701, 824
- O'Connor B. et al., 2023, *Sci. Adv.*, 9, eadi1405
- Ofek E. O. et al., 2007, *ApJ*, 662, 1129
- Ofek E. O. et al., 2023, *PASP*, 135, 065001
- Oke J. B., Gunn J. E., 1983, *ApJ*, 266, 713
- Oke J. B. et al., 1995, *PASP*, 107, 375
- Paciesas W. S. et al., 1999, *ApJS*, 122, 465
- Page M. J. et al., 2019, *MNRAS*, 488, 2855
- Pasham D. R. et al., 2023, *Nat. Astron.*, 7, 88
- Perley D. A., 2019, *PASP*, 131, 084503
- Perley D. A. et al., 2008, *ApJ*, 688, 470
- Perley R. A., Chandler C. J., Butler B. J., Wrobel J. M., 2011, *ApJ*, 739, L1
- Perley D. A. et al., 2014, *ApJ*, 781, 37
- Perna R., Loeb A., 1998, *ApJ*, 509, L85
- Pescalli A., Ghirlanda G., Salafia O. S., Ghisellini G., Nappo F., Salvaterra R., 2015, *MNRAS*, 447, 1911
- Piran T., 2004, *Rev. Mod. Phys.*, 76, 1143
- Rastinejad J. C. et al., 2022, *Nature*, 612, 223
- Rau A., Ofek E. O., Kulkarni S. R., Madore B. F., Pevunova O., Ajello M., 2008, *ApJ*, 682, 1205
- Rees M. J., Meszaros P., 1994, *ApJ*, 430, L93
- Rhoads J. E., 1997, *ApJ*, 487, L1
- Rhoads J. E., 2003, *ApJ*, 591, 1097
- Rhodes L. et al., 2023, *MNRAS*, 521, 389
- Ricker G. R. et al., 2015, *J. Astron. Telesc. Instrum. Syst.*, 1, 014003
- Rossi E., Lazzati D., Rees M. J., 2002, *MNRAS*, 332, 945
- Rykoff E. S. et al., 2009, *ApJ*, 702, 489
- Salafia O. S., Ghirlanda G., 2022, *Galaxies*, 10, 93
- Salafia O. S., Ghisellini G., Pescalli A., Ghirlanda G., Nappo F., 2015, *MNRAS*, 450, 3549
- Salafia O. S., Barbieri C., Ascenzi S., Toffano M., 2020, *A&A*, 636, A105
- Sari R., Piran T., 1999, *ApJ*, 520, 641
- Sarin N., Hamburg R., Burns E., Ashton G., Lasky P. D., Lamb G. P., 2022, *MNRAS*, 512, 1391
- Schlafly E. F., Finkbeiner D. P., 2011, *ApJ*, 737, 103
- Schulze S. et al., 2014, *A&A*, 566, A102
- Singer L. P. et al., 2013, *ApJ*, 776, L34
- Soderberg A. M. et al., 2004, *Nature*, 430, 648
- Soderberg A. M. et al., 2010, *Nature*, 463, 513
- Stalder B. et al., 2017, *ApJ*, 850, 149
- Swain V., Andreoni L., Coughlin M., Kumar H., Salgundi A., 2023, *Transient Name Server AstroNote*, 2023-178
- Troja E. et al., 2022, *Nature*, 612, 228
- Vail J. L., Li M. L., Wise J., Perley D. A., Ho A. Y. Q., Burns E., Coughlin M., 2023, *Transient Name Server AstroNote*, 2023-251
- Vanderspek R., Doty J. P., Fausnaugh M., Villasenor J. N. S., Jenkins J. M., Berta-Thompson Z. K., Burke C. J., Ricker G. R., 2018, *TESS Instrument Handbook*, v0.1, https://archive.stsci.edu/files/live/sites/mast/files/home/missions-and-data/active-missions/teess/_documents/TESS_Instrument_Handbook_v0.1.pdf
- van Roestel J. et al., 2019, *Res. Notes Am. Astron. Soc.*, 3, 136
- van Paradijs J., Kouveliotou C., Wijers R. A. M. J., 2000, *ARA&A*, 38, 379
- Virgili F. J., Liang E.-W., Zhang B., 2009, *MNRAS*, 392, 91
- Walker M. A., 1998, *MNRAS*, 294, 307
- Walker M. A., 2001, *MNRAS*, 321, 176
- Willingale R., Starling R. L. C., Beardmore A. P., Tanvir N. R., O'Brien P. T., 2013, *MNRAS*, 431, 394
- Woosley S. E., Bloom J. S., 2006, *ARA&A*, 44, 507
- Xu F., Huang Y.-F., Geng J.-J., 2023, *A&A*, 679, A103
- Yang J. et al., 2022, *Nature*, 612, 232
- Yang Y.-H. et al., 2024, *Nature*, 626, 742
- Yao Y., Lu W., Harrison F., Kulkarni S. R., Gezari S., Guolo M., Cenko S. B., Ho A. Y. Q., 2024, *ApJ*, 965, 39
- Yonetoku D. et al., 2014, in Takahashi T., den Herder J.-W. A., Bautz M., eds, Proc. SPIE Conf. Ser. Vol. 9144, *Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray*. SPIE, Bellingham, p. 91442S,
- Zauderer B. A. et al., 2011, *Nature*, 476, 425
- Zhang B., Mészáros P., 2002, *ApJ*, 571, 876
- Zhang B., Zhang B.-B., Liang E.-W., Gehrels N., Burrows D. N., Mészáros P., 2007, *ApJ*, 655, L25
- Zitouni H., Daigne F., Mochkovich R., Zerguini T. H., 2008, *MNRAS*, 386, 1597

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