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# iPTF14yb: THE FIRST DISCOVERY OF A GAMMA-RAY BURST AFTERGLOW INDEPENDENT OF A HIGH-ENERGY TRIGGER

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## ABSTRACT

We report here the discovery by the Intermediate Palomar Transient Factory (iPTF) of iPTF14yb, a luminous ($M_r \approx -27.8$ mag), cosmological (redshift 1.9733), rapidly fading optical transient. We demonstrate, based on probabilistic arguments and a comparison with the broader population, that iPTF14yb is the optical afterglow of the long-duration gamma-ray burst GRB 140226A. This marks the first unambiguous discovery of a GRB afterglow prior to (and thus entirely independent of) an associated high-energy trigger. We estimate the rate of iPTF14yb-like sources (i.e., cosmologically distant relativistic explosions) based on iPTF observations, inferring an all-sky value of $\mathfrak{R}_{\rm rel} = 610$ yr$^{-1}$ (68% confidence interval of 110–2000 yr$^{-1}$). Our derived rate is consistent (within the large uncertainty) with the all-sky rate of on-axis GRBs derived by the *Swift* satellite. Finally, we briefly discuss the implications of the nondetection to date of bona fide "orphan" afterglows (i.e., those lacking detectable high-energy emission) on GRB beaming and the degree of baryon loading in these relativistic jets.

*Key words:* gamma-ray burst: general – stars: flare – supernovae: general

## 1. INTRODUCTION

Two central tenets of our standard model of long-duration gamma-ray bursts (GRBs) hold that these explosions are ultrarelativistic (initial Lorentz factor $\Gamma_0 \gtrsim 100$) and highly collimated (biconical jets with half-opening angle $\theta \approx 1$–$10°$). The former is invoked to explain the so-called "compactness" problem: absent this ultrarelativistic expansion, the ejecta would be optically thick to pair production at typical peak spectral energies of a few 100 keV, whereas the prompt emission is observed to be nonthermal.[24] On the other hand, a high degree of collimation is required for basic energy conservation: the isotropic energy release can in some cases exceed $10^{54}$ erg, comparable to the rest-mass energy of their massive-star progenitors.

In order to accelerate material to these velocities, the outgoing jet must entrain a very small amount of mass ($M_{\rm ej} \approx 10^{-5}\, M_\odot$); this is referred to as the "baryon loading" of the jet. Most *observed* GRB prompt spectra, with peak spectral energies of a few 100 keV, therefore indicate very "clean" outflows (i.e., low mass of entrained baryons; Meszaros & Rees 1992). But there is growing evidence that the intrinsic population of long GRBs is dominated by bursts with peak energies below the traditional $\gamma$-ray bandpass (e.g., Ramirez-Ruiz et al. 2005; Butler et al. 2010). Could these lower $E_{\rm pk}$, fainter outbursts (e.g., X-ray flashes; Heise et al. 2001) result

[23] Hubble Fellow.
[24] More recently, a possible photospheric component has been identified in the prompt high-energy spectra of a number of GRBs (e.g., Ryde et al. 2010; Guiriec et al. 2011), but this does not dramatically ease the requirement of ultrarelativistic expansion.

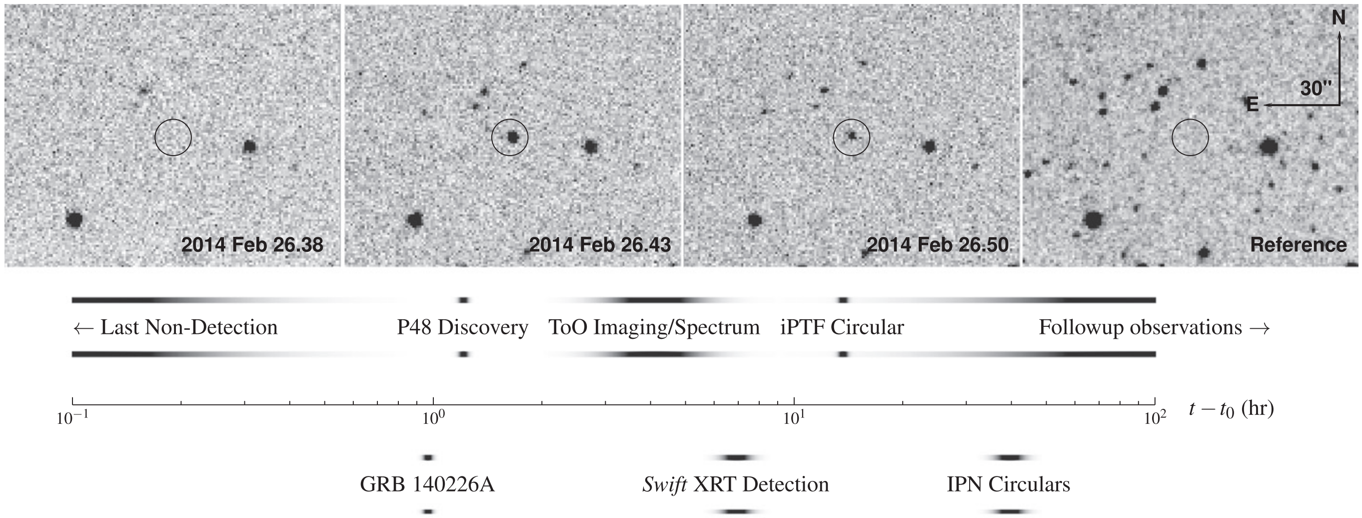


**Figure 1.** Top: P48 discovery images of iPTF14yb. The circle marks the location of iPTF14yb. Bottom: timeline of iPTF14yb/GRB 140226A discovery and announcements.

from an outflow with more entrained mass (i.e., a "dirty" fireball; Dermer et al. 2000; Huang et al. 2002)? Or can other properties, such as viewing angle (Granot et al. 2005) or the nature of the remnant (Mazzali et al. 2006), account for these softer events?

Separately, the high degree of collimation requires that most ($f_b \equiv (1 - \cos\langle\theta\rangle)^{-1} \approx 100$; Guetta & Della Valle 2007) GRBs are in fact beamed away from us on Earth. The afterglows of these off-axis bursts become visible at late times ($t \gg \Delta t_{\rm GRB}$) when the outflow slows down and illuminates an increasing fraction of the sky (Rhoads 1999; Sari et al. 1999). Yet despite concerted efforts at uncovering such orphan afterglows in the X-ray (Greiner et al. 2000; Nakar & Piran 2003; Law et al. 2004), optical (Becker et al. 2004; Rykoff et al. 2005; Rau et al. 2006), and radio (Gal-Yam et al. 2006) bandpasses, no bona fide off-axis candidate has been identified thus far.

All of these issues can be addressed by sensitive, wide-field surveys that target relativistic explosions independent of any high-energy trigger. To that end, we present here the discovery by the Intermediate Palomar Transient Factory (iPTF; Law et al. 2009) of iPTF14yb, a luminous ($M_r \approx -27.8$ mag), rapidly fading optical transient at redshift $z = 1.9733$. We demonstrate that this object is very likely associated with GRB 140226A, making iPTF14yb the first unambiguous example of a GRB afterglow discovered independent of a high-energy trigger.

Throughout this work, we adopt a standard ΛCDM cosmology with parameters from Planck Collaboration et al. (2014). All quoted uncertainties are $1\sigma$ (68%) confidence intervals unless otherwise noted, and UTC times are used throughout.

## 2. DISCOVERY AND FOLLOW-UP OBSERVATIONS

As part of regular monitoring observations with the Palomar 48 inch Oschin Schmidt telescope (P48)[25], we discovered a new transient source, designated iPTF14yb, at J2000.0 location $\alpha = 14^{\rm h}45^{\rm m}58\overset{\rm s}{.}01$, $\delta = +14°59'35\overset{''}{.}1$ (estimated uncertainty of 80 mas in each coordinate; Figure 1). iPTF14yb was first detected in a 60 s image beginning at 10:17:37 on 2014 February 26, with a magnitude of $r' = 18.16 \pm 0.03$. Subsequent P48 monitoring revealed rapid intranight fading from the source (Figure 2).

Nothing was detected at the location of iPTF14yb in a P48 image beginning at 09:04:46 on 2014 February 26 (i.e., 1.21 hr before the first detection) to a limit of $r' > 21.16$ mag. A coaddition of all existing iPTF P48 images of this location, spanning the time range from 2009 May 28 to 2014 February 24, also reveals no quiescent counterpart to $r' > 22.9$ mag (Figure 1).

Motivated by the rapid fading and lack of a quiescent counterpart, the duty astronomer (A. Rubin) distributed an immediate alert to the collaboration. We triggered multi-wavelength follow-up observations at a variety of facilities. We report here photometry obtained with the Triple-Range Imager and POLarimeter (TRIPOL) on the 1 m telescope at Lulin Observatory, the Gamma-Ray Burst Optical/Near-Infrared Detector (GROND; Greiner et al. 2008) on the 2.2 m telescope at ESO La Silla, the Reionization and Transients InfraRed camera (RATIR; Butler et al. 2012; Fox et al. 2012) on the 1.5 m telescope on San Pedro Martir, the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the 10 m Keck I telescope, the Inamori-*Magellan* Areal Camera and Spectrograph (IMACS; Dressler et al. 2011) on the 6 m Baade telescope at Las Campanas Observatory, and the DEep Imaging Multi-Object Spectrograph (DEIMOS; Faber et al. 2003) on the 10 m Keck II telescope. All imaging data were reduced in the standard manner and calibrated with respect to nearby point sources from the Sloan Digital Sky Survey (SDSS; Ahn et al. 2014) in the optical and 2MASS (Skrutskie et al. 2006) in the near-infrared. The resulting photometry is displayed in Table 1, while the *R*/*r*-band light curve is plotted in Figure 2.

We obtained target-of-opportunity X-ray observations with the *Swift* satellite (Gehrels et al. 2004) beginning at 17:11 on 2014 February 26. A bright counterpart was identified in the X-Ray Telescope (XRT; Burrows et al. 2005) images at the

[25] P48 data processing is described by Laher et al. (2014), while photometric calibration of iPTF data is discussed by Ofek et al. (2012).

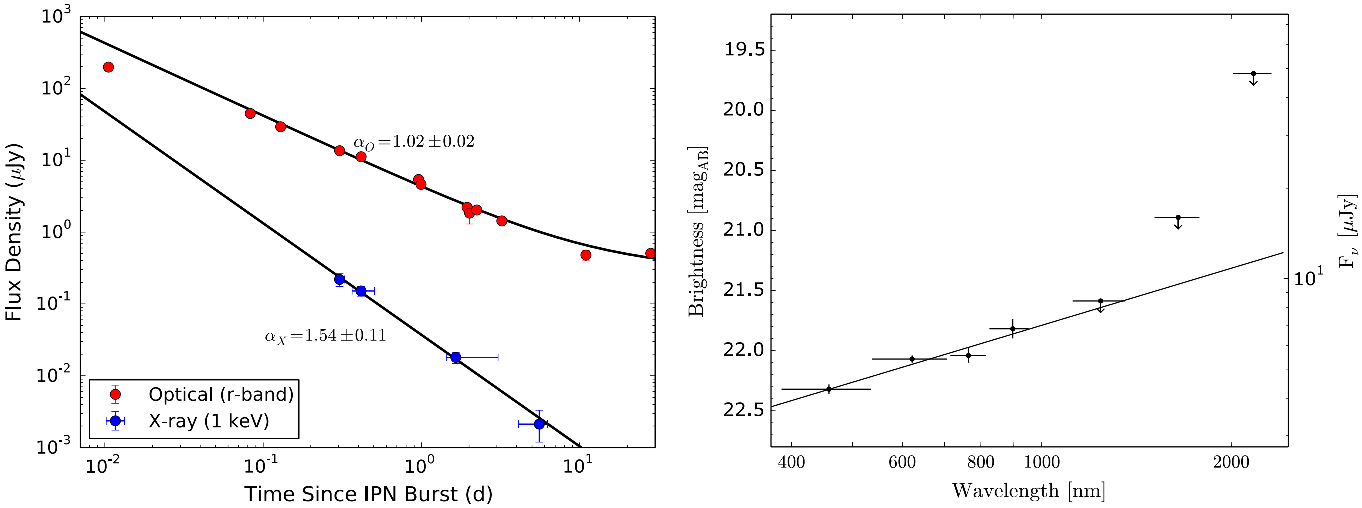


**Figure 2.** Right: optical ($r$-band) and X-ray light curves of iPTF14yb. The outburst onset is taken as the time of the IPN GRB 140226A. Left: optical/near-infrared SED at $\Delta t = 1.0$ day.

location of iPTF14yb. The resulting light curve, processed with the automated GRB analysis tools of Evans et al. (2009), is plotted in Figure 2. The X-ray spectrum is well described by a power law with a photon index $\Gamma = 2.1^{+0.5}_{-0.3}$.

The position of iPTF14yb was observed with the Karl G. Jansky Very Large Array[26] (VLA) in its A configuration under program 14A-483 (PI: S. Kulkarni). Two epochs were obtained, one on 2014 February 27.7 ($C$- and $K$-bands), and one on 2014 March 25.4 ($C$-band). Both observations were conducted with the standard wide-band continuum imaging setup. We used 3C 286 and J1446+1721 for flux and phase calibration, respectively. No radio emission was detected from iPTF14yb to the following $3\sigma$ limits: $f_\nu(6\,\mathrm{GHz}) < 45\,\mu$Jy (February 27); $f_\nu(22\,\mathrm{GHz}) < 153\,\mu$Jy (February 27); $f_\nu(6\,\mathrm{GHz}) < 16\,\mu$Jy. Similarly, observations with the Combined Array for Research in Millimeter Astronomy (CARMA) on 2014 February 28.5 failed to detect any emission at 95 GHz to a $3\sigma$ limit of <0.75 mJy.

Finally, we obtained a CCD spectrum of iPTF14yb with LRIS beginning at 15:26 on 2014 February 26. The instrument was configured with the 400/8500 grating on the red arm, the 600/4000 grism on the blue arm, the 560 dichroic beamsplitter, and a 1″ wide slit. As a result, our spectrum provides continuous coverage from the atmospheric cutoff ($\lambda \approx 3250$ Å) to 10,200 Å, with a spectral resolution of 7.1 (4.0) Å on the red (blue) arm. The resulting one-dimensional spectrum is plotted in Figure 3.

Superimposed on a relatively flat continuum ($f_\lambda \propto \lambda^{-1.3\pm0.1}$), we identify strong metal absorption lines from Mg II, Fe II, Al II, C IV, Si II, Si IV, C II, and O I at $z = 1.9733 \pm 0.0003$. A damped Ly$\alpha$ (DLA) system with $\log(N_{\mathrm{H\,I}}/\mathrm{cm}^2) = 20.7 \pm 0.2$ is also observed at this redshift, and the onset of the Ly$\alpha$ forest blueward of H I implies that this is the redshift of iPTF14yb.

## 3. ASSOCIATION WITH GRB 140226A

Following notification of our discovery of iPTF14yb, the Inter-Planetary Network of high-energy detectors (IPN; Hurley et al. 2010) reported the discovery of GRB 140226A, a possible counterpart of iPTF14yb (Hurley et al. 2014). GRB 140226A was detected by the *Odyssey*, *INTEGRAL*, and *Konus* satellites at 10:02:57 on 2014 February 26; this is 14.7 minutes before the midpoint of our P48 discovery image, and 58.2 minutes after our last P48 nondetection. The *Konus* light curve[27] shows a single pulse with a duration of 15 s (i.e., a long-duration GRB), and a 20 keV–10 MeV $\gamma$-ray fluence of $(5.6 \pm 1.1) \times 10^{-6}$ erg cm$^{-2}$ (Golenetskii et al. 2014). At this time, the location of iPTF14yb was below the horizon for the Burst Alert Telescope (BAT) onboard *Swift*, while the Gamma-Ray Burst Monitor (GBM) on *Fermi* was turned off owing to passage through the South Atlantic Anomaly (Hurley et al. 2014).

We can estimate the a posteriori probability of chance coincidence, both spatially and temporally. The IPN localized GRB 140226A to an annulus with an area of 210 deg$^2$ (Hurley et al. 2014). Thus, the likelihood of chance spatial association is ~0.005. Similarly, since 2010 January 1, the IPN has been detecting GRBs at a rate of ~0.88 days$^{-1}$. Therefore, the likelihood of an unrelated IPN GRB being detected within the 73 minute period between the last P48 upper limit and the first detection of iPTF14yb is ~0.044. Hence, the joint probability of chance coincidence is quite small, $\sim 2 \times 10^{-4}$. We conclude that iPTF14yb is very likely associated with GRB 140226A and shall proceed with this assumption for the remainder of this work.

## 4. iPTF14yb IN THE LONG-DURATION GRB CONTEXT

We now compare the observed properties of iPTF14yb and its host galaxy with the known population of long-duration GRBs as a final consistency check. We fit the X-ray light curve to a power law of the form $f_\nu \propto t^{-\alpha}$, finding $\alpha_X = 1.54 \pm 0.11$ ($\chi^2 = 0.46$ for two degrees of freedom, dof). At late times ($\Delta t \gtrsim 10$ days), the observed optical decay flattens, and in our last DEIMOS image the emission at the transient location is clearly spatially resolved. We interpret this to result from the emergence of an underlying host galaxy with $R \gtrsim 24.6$ mag. Neglecting the first point in the $R$/$r$-band light

[26] The National Radio Astronomy Observatory is a facility of the National Science Foundation (NSF) operated under cooperative agreement by Associated Universities, Inc.

[27] See http://www.ioffe.rssi.ru/LEA/GRBs/GRB140226A.

**Table 1**
Optical/Near-infrared Observations of iPTF14yb

| Date (MJD) | Telescope/ Instrument | Filter | Exposure Time (s) | Magnitude[a] |
|---|---|---|---|---|
| 56714.379 | P48/CFHT12k | $r$ | 60.0 | >21.16 |
| 56714.429 | P48/CFHT12k | $r$ | 60.0 | $18.16 \pm 0.03$ |
| 56714.502 | P48/CFHT12k | $r$ | 60.0 | $19.77 \pm 0.07$ |
| 56714.548 | P48/CFHT12k | $r$ | 60.0 | $20.24 \pm 0.08$ |
| 56714.723 | Lulin/TRIPOL | $g'$ | 2400.0 | $21.17 \pm 0.13$ |
| 56714.723 | Lulin/TRIPOL | $r'$ | 2400.0 | $21.07 \pm 0.11$ |
| 56714.723 | Lulin/TRIPOL | $i'$ | 2400.0 | $20.79 \pm 0.11$ |
| 56714.835 | Lulin/TRIPOL | $g'$ | 2700.0 | $21.61 \pm 0.18$ |
| 56714.835 | Lulin/TRIPOL | $r'$ | 2700.0 | $21.28 \pm 0.13$ |
| 56714.835 | Lulin/TRIPOL | $i'$ | 2700.0 | $21.00 \pm 0.11$ |
| 56715.379 | La Silla/GROND | $g'$ | 869.9 | $22.32 \pm 0.04$ |
| 56715.379 | La Silla/GROND | $r'$ | 869.9 | $22.07 \pm 0.03$ |
| 56715.379 | La Silla/GROND | $i'$ | 869.9 | $22.04 \pm 0.06$ |
| 56715.379 | La Silla/GROND | $z'$ | 869.9 | $21.82 \pm 0.08$ |
| 56715.379 | La Silla/GROND | $J$ | 869.9 | >21.6 |
| 56715.379 | La Silla/GROND | $H$ | 869.9 | >21.0 |
| 56715.379 | La Silla/GROND | $K$ | 869.9 | >19.8 |
| 56715.413 | SPM/RATIR | $r'$ | 14076.0 | $22.24 \pm 0.09$ |
| 56715.413 | SPM/RATIR | $i'$ | 14076.0 | $21.99 \pm 0.09$ |
| 56715.413 | SPM/RATIR | $z'$ | 5904.0 | $21.96 \pm 0.24$ |
| 56715.413 | SPM/RATIR | $Y$ | 5904.0 | $22.10 \pm 0.35$ |
| 56715.413 | SPM/RATIR | $J$ | 5904.0 | $21.87 \pm 0.35$ |
| 56715.413 | SPM/RATIR | $H$ | 5904.0 | >21.58 |
| 56716.362 | La Silla/GROND | $g'$ | 1871.3 | $23.15 \pm 0.06$ |
| 56716.362 | La Silla/GROND | $r'$ | 1871.3 | $23.04 \pm 0.06$ |
| 56716.362 | La Silla/GROND | $i'$ | 1871.3 | $22.82 \pm 0.11$ |
| 56716.362 | La Silla/GROND | $z'$ | 1871.3 | $22.66 \pm 0.11$ |
| 56716.362 | La Silla/GROND | $J$ | 1871.3 | >21.5 |
| 56716.362 | La Silla/GROND | $H$ | 1871.3 | >20.9 |
| 56716.362 | La Silla/GROND | $K$ | 1871.3 | >19.8 |
| 56716.435 | SPM/RATIR | $r'$ | 9468.0 | $23.24 \pm 0.32$ |
| 56716.435 | SPM/RATIR | $i'$ | 9468.0 | $22.48 \pm 0.20$ |
| 56716.435 | SPM/RATIR | $z'$ | 4032.0 | >22.09 |
| 56716.435 | SPM/RATIR | $Y$ | 4032.0 | >21.72 |
| 56716.656 | Keck I/LRIS | $g'$ | 540.0 | $23.21 \pm 0.04$ |
| 56716.656 | Keck I/LRIS | $R$ | 480.0 | $23.13 \pm 0.05$ |
| 56717.641 | Keck I/LRIS | $g'$ | 720.0 | $23.68 \pm 0.02$ |
| 56717.642 | Keck I/LRIS | $R$ | 640.0 | $23.51 \pm 0.03$ |
| 56725.373 | Baade/IMACS | $R$ | 1500.0 | $24.70 \pm 0.19$ |
| 56742.557 | Keck II/DEIMOS | $R$ | 2100.0 | $24.64 \pm 0.09$ |

[a] Reported magnitudes are in the AB system and have been corrected for a foreground Galactic extinction of $E(B - V) = 0.016$ mag (Schlafly & Finkbeiner 2011).

curve (where the decay appears shallower), we find an optical decay index of $\alpha_O = 1.02 \pm 0.02$ ($\chi^2 = 61.3$ for 10 dof). The simultaneous GROND optical/near-infrared spectral energy distribution (SED) at $\Delta t = 1.0$ day is well fit by a power law with index $\beta_O = 0.63 \pm 0.10$ with no evidence for extinction in the host galaxy (Figure 2). All these results are broadly consistent with standard afterglow models (e.g., Granot & Sari 2002) for expansion into a constant-density circumburst medium with electron index $p \approx 2.5$ and a cooling break between the X-ray and optical bands (though close to the X-rays, as the derived X-ray to optical spectral index at $\Delta t = 1$ day, $\beta_{OX} = 0.86$, is comparable to $\beta_X = 1.1^{+0.5}_{-0.3}$). Furthermore, these properties are typical of early X-ray (e.g., Evans et al. 2009) and optical (e.g., Cenko et al. 2009) afterglow light-curve behavior.

The temporal decay indices observed in the X-ray and (especially) the optical are difficult to reconcile with post-jet-break evolution (e.g., Sari et al. 1999), as would be expected for an off-axis orphan afterglow ($\alpha_{\rm orphan} \gtrsim 2$).[28] Together with the rapid rise from our P48 nondetection 1.2 hr before discovery, this further reinforces the association with GRB 140226A, as it suggests iPTF14yb was initially viewed from within the jet opening angle. The emergence of the host galaxy in the optical at $\Delta t \approx 10$ days greatly complicates our ability to detect any jet-break feature in the afterglow light curve, which would have offered robust support for such a geometry.

Finally, the observed optical spectrum is typical of low-resolution spectra of the afterglows of long-duration GRBs (e.g., Fynbo et al. 2009), with DLA absorption and strong features from both low- and high-ionization-state metal transitions. Unlike many other GRB afterglows, however, no fine-structure lines are apparent in the spectrum of iPTF14yb. This may be caused either by absorbing material that is more distant from the explosion site, or simply a lack of sensitivity (in particular, spectral resolution).

## 5. THE RATE OF RELATIVISTIC TRANSIENTS

Based on the results of the last two sections, we consider the association between iPTF14yb and GRB 140226A to be extremely robust. This marks the first time that a bona fide GRB afterglow (i.e., a cosmologically distant, ultrarelativistic explosion) has been identified prior to (and entirely independent of) a high-energy trigger. While undoubtedly a technical achievement, we are more interested in what limits from the *nondetection* of other, more exotic explosions may tell us about relativistic jet formation and collimation.

Predictions for the rate of off-axis orphan-afterglow detection vary significantly depending on underlying model assumptions (e.g., average opening angle, degree of lateral spreading of the ejecta). For example, at magnitude levels accessible to iPTF (peak $r \lesssim 20$), Totani & Panaitescu (2002) predicted that off-axis afterglows should outnumber on-axis GRBs by a factor of 3:1. On the other hand, Nakar et al. (2002) find that on-axis GRBs will outnumber off-axis orphans for optical surveys with a limiting magnitude shallower than ~23.

In addition, while a relativistic explosion may be both jetted and viewed on-axis, it may nonetheless lack prompt high-energy emission if the initial Lorentz factor is not sufficiently high to overcome pair-production opacity. Possible examples include nearby relativistic supernovae such SN 2009bb (Soderberg et al. 2010) and SN 2012ap (Chakraborti et al. 2014), as well as the fast-fading cosmological transient PTF11agg (Cenko et al. 2013).

To calculate the rate of relativistic transients, we assume here for simplicity that all events have light curves identical to that of iPTF14yb, and fold this through all P48 observations taken from 2013 January 1 through 2014 March 1. We only consider observations taken after 2013 January 1 as we implemented significant improvements to our real-time detection pipeline on that date. We emphasize that our software requires at least two detections with significance $>5\sigma$ to filter out minor planets and

[28] Even if we allow the outburst time to vary freely in our power-law fits, the best-fit temporal indices in the X-ray and optical are still $\lesssim 2.0$.

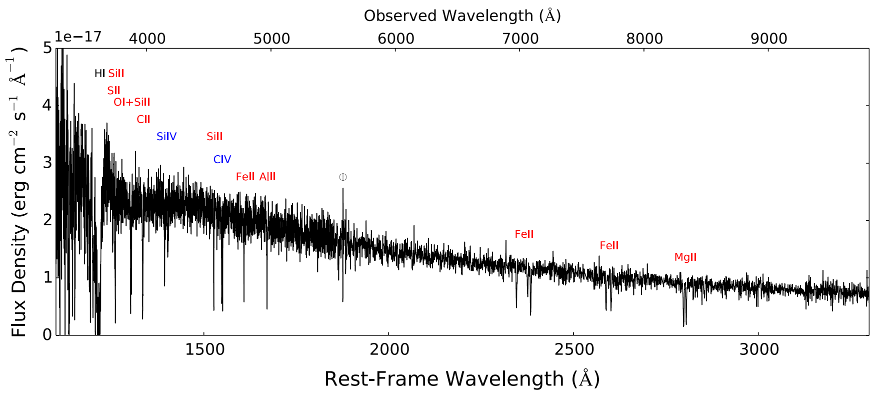


**Figure 3.** Keck/LRIS spectrum of iPTF14yb. Low-ionization (red labels) and high-ionization (blue labels) absorption lines from the host-galaxy interstellar medium, at a common redshift of 1.9733, are marked.

image artifacts, which does significantly reduce our sensitivity to such rapidly fading transients (roughly by a factor of two).

Altogether, we find a total areal exposure of $A_{\rm eff} = 24{,}637$ deg$^2$ days for iPTF14yb-like light curves. This implies an all-sky rate of relativistic transients of

$$\begin{aligned}\mathfrak{R}_{\rm rel} &\equiv \frac{N_{\rm rel}}{A_{\rm eff}}\\ &= \frac{1}{24{,}637\ {\rm deg}^2\ {\rm days}} \times \frac{365.25\ {\rm days}}{\rm yr} \times \frac{41{,}253\ {\rm deg}^2}{\rm sky}\\ &= 610\ {\rm yr}^{-1}.\end{aligned}$$

Assuming Poisson statistics, this implies a 68% confidence interval of (110–2000) yr$^{-1}$. We note that this value is actually a lower limit, as it assumes we are 100% efficient at *discovering* such sources in our data stream, even when they are significantly *detected* in our images. For the remainder of this work we assume our discovery efficiency, $\epsilon_{\rm rel}$, is $\sim$1; a more sophisticated analysis of the iPTF discovery efficiency suggests this is a reasonable approximation (A. L. Urban et al. 2015, in preparation).

As a sanity check, we can compare this to the rate of on-axis long-duration GRBs within the comoving volume out to $z \approx 3$ (the approximate distance to which P48 could detect iPTF14yb). According to the BAT trigger simulations performed by Lien et al. (2014), the all-sky rate of on-axis GRBs out to $z = 3$ is $\mathfrak{R}_{\rm GRB} = 1455^{+80}_{-112}$ yr$^{-1}$. However, only a fraction of these events will have optical afterglows bright enough to detect by iPTF. From unbiased samples of robotic follow-up observations of *Swift* afterglows with moderate-aperture facilities (e.g., Cenko et al. 2009; Greiner et al. 2011), we infer that approximately two-thirds of long-duration GRBs have optical afterglows accessible to P48 (peak $r \lesssim 20$ mag), or $\mathfrak{R}_{\rm AG} = 970^{+53}_{-74}$ yr$^{-1}$ GRBs. We conclude that our discovery rate is entirely consistent with the known population of on-axis *Swift* events.

Considering the comoving volume out to $z \approx 3$, we can estimate the volumetric rate of relativistic transients derived by iPTF to be $\rho_{\rm rel} = 0.54$ Gpc$^{-3}$ yr$^{-1}$. In addition to Poisson uncertainty in $\mathfrak{R}_{\rm rel}$, we include uncertainties on the value of $z_{\rm max}$: from 1.9733 (the redshift of iPTF14yb) to $\sim$6 (where neutral H from the intergalactic medium precludes optical detection). The resulting 68% confidence interval on $\rho_{\rm rel}$ is thus (0.043–3.25) Gpc$^{-3}$ yr$^{-1}$. We plot this value in Figure 4 as a function of characteristic survey time scale (e.g., cadence). While iPTF repeats field visits on a wide variety of time scales, we adopt here our typical internight cadence of 1 hr as representative for fast-fading sources. Shown for comparison are limits for luminous ($M \approx -27$ mag), rapidly fading optical transients from other surveys (Berger et al. 2013, and references therein). These reported limits likely underestimate the sensitivity of these surveys to iPTF14yb-like transients, possibly by as much as an order of magnitude; for example, iPTF14yb would be detectable by PS1/MDS for approximately 1 day, significantly longer than the 30 minute cadence. Nonetheless, by comparing with the all-sky rate of *Swift* GRBs out to $z = 3$ from Lien et al. (2014), it is clear that iPTF is the first optical survey with sufficient sensitivity to detect on-axis GRBs independent of any high-energy trigger.

Even with the relatively simple analysis performed here, our derived limits appear to disfavor (though not entirely rule out) the most optimistic predictions for off-axis orphan afterglows (e.g., Totani & Panaitescu 2002). Furthermore, the rate of on-axis orphans (i.e., dirty fireballs) can also not be dramatically higher than the rate of long-duration GRBs, as was previously argued based on the discovery of PTF11agg (Cenko et al. 2013); see Greiner et al. (2000) for analogous limits in the X-rays. A more detailed analysis would require, for example, more realistic models of the afterglow luminosity function, redshift distribution, off-axis emission, etc enabling more robust limits to be placed on the typical GRB beaming angle and the optimal strategy for orphan searches with future wide-field optical surveys. Such an analysis is planned in a future work (A. L. Urban et al. 2015, in preparation).

Nonetheless, it is an exciting time in the search for orphan afterglows. As several new wide-field optical transient surveys such as the Zwicky Transient Facility and the Large Synoptic Survey Telescope prepare to see first light, the first bona fide detection is almost guaranteed to arrive in the coming years. Future proposed wide-field space missions such as ULTRASAT[29] would carry out sensitive searches for orphan afterglows as well. Furthermore, new wide-field radio surveys such as the Murchison Wide-Field Array, the Australian Square Kilometer Array Pathfinder, and South African MeerKAT radio telescope, promise an even more powerful census of relativistic explosions (though identifying them may prove quite challenging, given their slow evolution at late times). iPTF14yb represents

[29] See http://www.weizmann.ac.il/astrophysics/ultrasat.

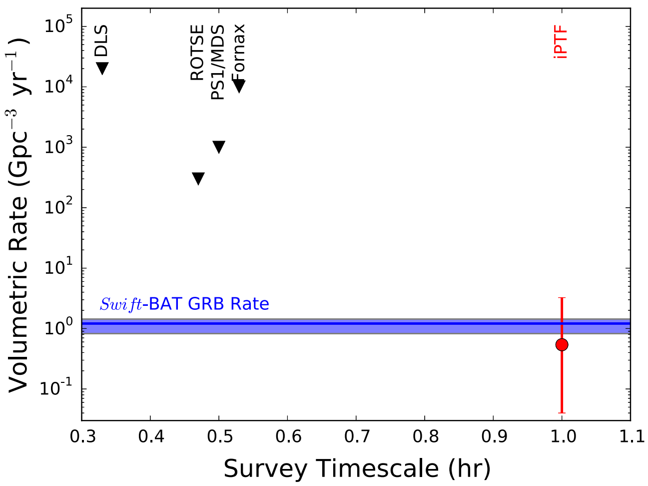


**Figure 4.** Rate of fast, luminous ($M \approx -27$ mag) optical transients, from iPTF and other surveys (Berger et al. 2013 and references therein). The all-sky *Swift* BAT GRB rate out to $z \approx 3$ is taken from Lien et al. (2014).

not only a technical milestone in fast-transient science, but also an important proof of concept for orphan-afterglow searches.

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