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Authors
Holoien, TW-S
Huber, ME
Shappee, BJ
et al.

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PS18kh: A New Tidal Disruption Event with a Non-Axisymmetric Accretion Disk


Pan-STARRS

J. Bulger,2 T. B. Lowe,2 E. A. Magnier,2 A. S. B. Schultz,2 C. Z. Waters,2 M. Willman,2 D. Wright,13 and D. R. Young13

ASAS-SN

Subo Dong,15 J. L. Prieto,16,17 and Todd A. Thompson4,6

ATLAS

L. Denneau;2 H. Flewelling,2 A. N. Heinze,2 S. J. Smartt,13 K. W. Smith,13 B. Stalder,18 J. L. Tonry,2 and H. Weiland2

1The Observatories of the Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101, USA
2Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
3Department of Astronomy & Astrophysics and Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA
4Center for Cosmology and AstroParticle Physics (CCAPP), The Ohio State University, 191 W. Woodruff Ave., Columbus, OH 43210, USA
5Department of Physics, The Ohio State University, 191 W. Woodruff Avenue, Columbus, OH 43210, USA
6Department of Astronomy, The Ohio State University, 140 West 18th Avenue, Columbus, OH 43210, USA
7Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA.
8Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA.
9Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK
10Post Observatory, Lexington, MA 02421, USA
11Lawrence Berkeley National Laboratory, Physics Division, One Cyclotron Rd, Berkeley, CA 94720, USA
12Berkeley Center for Cosmological Physics, 341 Campbell Hall, University of California Berkeley, Berkeley, CA 94720, USA
13Astrophysics Research Centre, School of Mathematics and Physics, Queens University Belfast, Belfast BT7 1NN, UK
14Division of Physics, Mathematics and Astronomy, California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125, USA
15Kavli Institute for Astronomy and Astrophysics, Peking University, Yi He Yuan Road 5, Hui Dian District, Beijing 100871, China
16Núcleo de Astronomía de la Facultad de Ingeniería y Ciencias, Universidad Diego Portales, Av. Ejército 441, Santiago, Chile
17Millennium Institute of Astrophysics, Santiago, Chile
18LSST, 950 North Cherry Avenue, Tucson, AZ 85719, USA

(Dated: August 15, 2018)

ABSTRACT

We present the discovery of PS18kh, a tidal disruption event (TDE) discovered at the center of SDSS J075654.53+341543.6 ($d \approx 337$ Mpc) by the Pan-STARRS Survey for Transients. Our dataset includes pre-discovery survey data from Pan-STARRS, the All-Sky Automated Survey for Supernovae (ASAS-SN), and the Asteroid Terrestrial-impact Last Alert System (ATLAS) as well as high-cadence, multi-wavelength follow-up data from ground-based telescopes and Swift, spanning from 56 days before peak light until 75 days after. The optical/UV emission from PS18kh is well-fit as a blackbody with temperatures ranging from $T \approx 14000$ K to $T \approx 22000$ K and it peaked at a luminosity of $L \approx 9.8 \times 10^{43}$ ergs s$^{-1}$. PS18kh radiated $E = (3.82 \pm 0.25) \times 10^{50}$ ergs over the period of observation, with $(1.58 \pm 0.22) \times 10^{50}$ ergs being released during the rise to peak. Spectra of PS18kh show a changing, boxy/double-peaked H$\alpha$ emission feature, which becomes more prominent over time. Using a wind-elliptical disk+spiral arm model, we model the physical properties of the accretion disk and the stellar debris following the disruption of the star, finding that the stellar...
debris initially absorbs the emission from the disk but becomes optically thin over time. The disk has an inner radius of \( r_{\text{in}} \sim 500r_g \) and an outer radius of \( r_{\text{out}} \sim 15000r_g \).

**Keywords:** accretion, accretion disks — black hole physics — galaxies: nuclei

1. INTRODUCTION

Tidal disruption events (TDEs) occur when a star crosses the tidal radius of a supermassive black hole (SMBH) and the tidal shear forces of the SMBH are able to overcome the self-gravity of the star. For main-sequence stars, approximately half of the stellar material is ejected from the system, while the other half remains bound to the SMBH. The bound material falls back to pericenter at a rate proportional to \( t^{-5/3} \) and a fraction of it is accreted onto the black hole, resulting in a short-lived, luminous flare (e.g., Lacy et al. 1982; Rees 1988; Evans & Kochanek 1989; Phinney 1989).

Initially, it was commonly assumed that the flare emission would peak at soft X-ray energies and that the luminosity would be proportional to the \( t^{-5/3} \) rate of return of the stellar material to pericenter. However, in recent years a number of well-studied TDEs have been discovered that exhibit a wide range of observational properties (e.g., van Velzen et al. 2011; Cenko et al. 2012; Gezari et al. 2012; Arcavi et al. 2014; Chornock et al. 2014; Holoien et al. 2014; Gezari et al. 2015; Vinko et al. 2015; Holoien et al. 2016b,a; Brown et al. 2016; Auchettl et al. 2017; Blagorodnova et al. 2017; Brown et al. 2017a,b; Gezari et al. 2017; Holoien et al. 2018). It is now known that the emission depends on many factors, including the physical properties of the disrupted star (e.g., MacLeod et al. 2012; Kochanek 2016), the evolution of the accretion stream after disruption (e.g., Kochanek 1994; Strubbe & Quataert 2009; Guillochon & Ramirez-Ruiz 2013; Hayasakii et al. 2013, 2016; Piran et al. 2015; Shiokawa et al. 2015), and radiative transfer effects (e.g., Gaskell & Rojas Lobos 2014; Strubbe & Murray 2015; Roth et al. 2016; Roth & Kasen 2018). However, there have been few TDEs monitored in sufficient detail to directly infer these properties. In particular, most TDE candidates have been discovered after peak light, making it difficult to study the formation of the accretion disk and the evolution of the stellar debris.

Here we present the discovery of PS18kh, a TDE candidate discovered by the Pan-STARRS Survey for Transients\(^1\) (PSST; Chambers et al. 2016) on 2018 March 02 in the spectroskopically unobserved galaxy SDSS J075654.53+341543.6. The discovery was announced publicly on 2018 March 04 on the Transient Name Server (TNS) and given the designation AT 2018zr\(^2\). The discovery image indicated that the position of the transient was consistent with the nucleus of the host, with the Pan-STARRS coordinates lying within 0\(^{\prime}\)1 of the measured center of the host in SDSS.

The transient was first spectroscopically observed by the Spectral Classification of Astronomical Transients (SCAT, Tucker et al. 2018a) survey, which uses the SuperNova Integral Field Spectrograph (SNIFS; Lantz et al. 2004) on the University of Hawaii 88-inch telescope. The initial spectrum obtained on 2018 March 07 showed a blue continuum with no obvious emission or absorption features, and a second spectrum obtained on 2018 March 18 was very similar, with a strong blue continuum, but with the addition of possible broad Balmer emission lines (Tucker et al. 2018b). Based on these spectra, we obtained two additional low-resolution optical spectra on 2018 March 20 with the Wide Field Reimaging CCD Camera (WFCCCD) mounted on the Las Campanas Observatory du Pont 2.5-m telescope (3700 – 9600 Å, R ∼ 7 Å) and the Fast Spectrograph (FAST; Fabricant et al. 1998) mounted on the Fred L. Whipple Observatory Tillinghast 1.5-m telescope (3700 – 9000 Å, R ∼ 3 Å). Both of these spectra also suggested the presence of broad Balmer emission lines with a strong blue continuum, both features of TDEs (e.g., Arcavi et al. 2014), and Tucker et al. (2018b) publicly announced that PS18kh was a TDE candidate on 2018 March 24. Based on the H\(\alpha\) emission line, we estimate that PS18kh has a redshift of \( z = 0.074 \), corresponding to a luminosity distance of 337 Mpc (\( H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.29 \), \( \Omega_{\Lambda} = 0.71 \); see Section 3.1).

Based on the preliminary classification, we requested and were awarded target-of-opportunity (TOO) observations from the Neil Gehrels Swift Gamma-ray Burst Mission (Swift; Gehrels et al. 2004) UltraViolet and Optical Telescope (UVOT; Roming et al. 2005) and X-ray Telescope (XRT; Burrows et al. 2005). These observations confirmed that the transient was bright in the UV and appeared to have weak soft X-ray emission, so we began an extended multiwavelength monitoring campaign to characterize PS18kh. With a peak g-band magnitude of \( m_g \simeq 17.3 \), PS18kh was also well-observed by a number of ground-based optical surveys, and we include in our analysis multiwavelength pre- and post-discovery light curves from Pan-STARRS, the All-Sky Automated Survey for Supernovae (ASAS-SN; Shappee et al. 2014), and the Asteroid Terrestrial-impact Last Alert System (ATLAS; Tonry et al. 2018) spanning from 56 days before the peak of the light curve until it became Sun-constrained 75 days after peak, making this one of the best-sampled early light curves for a TDE candidate to-date.
In Section 2 we describe the available pre-outburst data for the host galaxy and fit the physical properties of the host. We also describe the new observations of the transient that were obtained by the Pan-STARRS, ASAS-SN, and ATLAS surveys and our follow-up campaign. In Section 3.1 we perform detailed measurements of the position of PS18kh within its host, its redshift, and the time of peak light. In Section 3.2 we analyze the photometric data and model the luminosity and temperature evolution of PS18kh. In Section 3.3 we analyze the spectroscopic evolution of PS18kh and model the boxy, double-peaked emission line profiles in an attempt to determine the physical properties of the TDE-SMBH system. Finally, in Section 4 we compare the properties of PS18kh to those of supernovae and other TDEs and summarize our findings.

2. OBSERVATIONS AND SURVEY DATA

2.1. Archival Data and Host Fits

We retrieved archival optical ugriz model magnitudes of SDSS J075654.53+341543.6 from SDSS Data Release 14 (DR14; Abolfathi et al. 2018) and infrared W1 and W2 magnitudes from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) AllWISE catalog. The host is not detected in archival data from, or was not previously observed by, the Two Micron All-Sky Survey (2MASS), Spitzer, Herschel, the Hubble Space Telescope (HST), the Chandra X-ray Observatory, the X-ray Multi-Mirror Mission (XMM-Newton), or the Very Large Array Faint Images of the Radio Sky at Twenty-cm (VLA FIRST) survey. It is also not detected in Galaxy Evolution Explorer (GALEX) UV data, but we obtain 3-sigma 6″0 upper limits on the UV magnitudes of NUV > 23.65 and FUV > 23.69 using single-epoch data obtained on 2008 January 19. The archival host magnitudes and limits are listed in Table 1.

To place constraints on any X-ray emission prior to the flare that could be indicative of an AGN, we take advantage of data from the ROSAT All-sky Survey (Voges et al. 1999). We do not detect X-ray emission associated with the position of the host galaxy with a 3-sigma upper limit on the count rate of $8 \times 10^{-3}$ counts s$^{-1}$. Assuming an absorbed power law redshifted to the distance of the host galaxy and a photon index similar to that of known AGN ($\Gamma = 1.75$; e.g., Tozzi et al. 2006; Marchesi et al. 2016; Liu et al. 2017b; Ricci et al. 2017), we derive a limit on the absorbed (unabsorbed) flux of $2.3 (2.6) \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.3-10.0 keV energy band. At the distance of PS18kh this flux limit corresponds to an X-ray luminosity of $3.2 \times 10^{42}$ ergs s$^{-1}$. This is lower than the average luminosity of known AGN (e.g., Ricci et al. 2017), suggesting that the host galaxy of PS18kh does not harbor a strong AGN.

We fit the spectral energy distribution (SED) of the host galaxy to the archival limits and magnitudes from GALEX, SDSS, and WISE using the publicly available Fitting and Assessment of Synthetic Templates (FAST; Kriek et al. 2009). For the fit we assumed a Cardelli et al. (1989) extinction law with $R_V = 3.1$ and a Galactic extinction of $A_V = 0.128$ mag (Schlafly & Finkbeiner 2011) and we adopted an exponentially declining star-formation history, a Salpeter initial mass function, and the Bruzual & Charlot (2003) stellar population models. In order to make a more robust estimate of the host SED and the uncertainties on its physical parameters, we generated 1000 realizations of the archival fluxes, perturbed by their respective uncertainties assuming Gaussian errors. Each realization was then modeled with FAST. The median and 68% confidence intervals on the host parameters from these 1000 realizations are: $M_*=1.4^{+0.3}_{-0.3} \times 10^{10}$ $\text{M}_\odot$, age = $4.5^{+1.4}_{-1.4}$ Gyr, and a star formation rate $SFR = 8^{+4}_{-2} \times 10^{-3}$ $\text{M}_\odot$ yr$^{-1}$. We scaled the stellar mass of SDSS J075654.53+341543.6 using the average stellar-mass-to-bulge-mass ratio from the hosts of ASASSN-14ae, ASASSN-14li, and ASASSN-15oi (Holoien et al. 2014, 2016b,a), to get a bulge mass estimate of $M_B \simeq 10^{9.5} \text{M}_\odot$. Using the $M_B-M_{BH}$ relation from McConnell & Ma (2013), we obtain a black hole mass of $M_{BH} = 10^{6.9}$ $\text{M}_\odot$, comparable to what has been found for other optical TDE host galaxies (e.g., Holoien et al. 2014, 2016b,a; Brown et al. 2017a; Wevers et al. 2017; Mockler et al. 2018).

Our photometric follow-up campaign includes ugriz photometry, for which the archival SDSS data can be used to subtract the host flux and isolate the transient flux. For the Swift UVOT and Johnson-Cousins BV data, there are no available

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Table 1. Archival Photometry of SDSS J075654.53+341543.6

<table>
<thead>
<tr>
<th>Filter</th>
<th>Magnitude</th>
<th>Uncertainty</th>
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</thead>
<tbody>
<tr>
<td>FUV</td>
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<td>—</td>
</tr>
<tr>
<td>NUV</td>
<td>&gt;23.65</td>
<td>—</td>
</tr>
<tr>
<td>u</td>
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<td>0.12</td>
</tr>
<tr>
<td>g</td>
<td>18.93</td>
<td>0.01</td>
</tr>
<tr>
<td>r</td>
<td>18.17</td>
<td>0.01</td>
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<tr>
<td>i</td>
<td>17.76</td>
<td>0.01</td>
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<tr>
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<tr>
<td>W1</td>
<td>15.19</td>
<td>0.94</td>
</tr>
<tr>
<td>W2</td>
<td>15.32</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Note—Archival model magnitudes of SDSS J075654.53+341543.6 from SDSS DR14 (ugriz) and PSF photometry magnitudes from the AllWISE catalog (W1 and W2). The GALEX NUV and FUV upper limits are 3-sigma upper limits measured with a 6″0 aperture from a single epoch of data obtained on 2008 January 19.
The Pan-STARRS1 telescope, located at the summit of Haleakala on Maui, has a 1.8-m diameter primary mirror with a f/4.4 Cassegrain focus. The telescope uses a wide-field 1.4 gigapixel camera mounted at the Cassegrain focus, consisting of 60 Orthogonal Transfer Array devices, each of which has a detector area of 4846 x 4868 pixels. The 10 micron pixels have a plate scale of 0".26, giving a full field-of-view area of 7.06 square degrees, with an active region of roughly 5 square degrees. Pan-STARRS1 uses the griz filters, which are similar to those of SDSS (Abazajian et al. 2009), with the redder y filter replacing the bluer SDSS u filter. The Pan-STARRS1 photometric system in discussed in detail in (Tonry et al. 2012).

Pan-STARRS1 images are processed with the Image Processing Pipeline (IPP; see details in Magnier et al. 2013). The IPP runs new images through successive stages of processing, including device “de-trending”, a flux-conserving warping to a sky-based image plane, masking and artefact location that involves bias and dark correction, flatfielding, and illumination correction obtained by rastering sources across the field of view (Waters et al. 2016). After determining an initial astrometric solution, corrected images are then warped onto the tangent plane of the sky using a flux-conserving algorithm, which involves mapping the camera pixels to a defined set of sky cells. For nightly processing, the zeropoints of the camera chips are set using a catalog of photometric reference stars from the “ubercal” analysis of the first reprocessing of the PS1 3π data (Schlafly et al. 2012; Magnier et al. 2013). The internal calibration of this catalog has a relative precision of roughly 1%, but the automated zeropoint applied in difference imaging is an average full-field zeropoint, which can result in variations across sky cells of up to ±0.15 magnitudes.

Transient searching is aided by having pre-existing sky images from the Pan-STARRS Sky Surveys (Chambers et al. 2016). The IPP creates difference images by subtracting stacked reference images from the PS1 3π from newly observed images, and transient sources are then identified by the IPP through analysis of the difference images (e.g., Huber et al. 2015). Catalog source files from the IPP are transferred from Hawaii to Belfast and ingested into a MySQL database. A series of quality cuts are implemented (McCrum et al. 2015; Smartt et al. 2016) together with a machine learning algorithm that distinguishes real sources from bogus sources (Wright et al. 2015). Sources are accumulated into unique objects and spatially cross-matched against all large catalogs, therefore providing both a real-bogus value and a classification of variable star, AGN, supernova, CV, or nuclear transient. The griz lightcurve presented in this manuscript was produced from this Pan-STARRS transient processing pipeline as described in McCrum et al. (2014, 2015) and Smartt et al. (2016). The Pan-STARRS1 griz photometry is presented in Table 3 and is shown in Figure 1; we do not present the y photometry as PS18kh was only detected in one y-band epoch.

### 2.2. Pan-STARRS light curve

The Pan-STARRS1 telescope, located at the summit of Haleakala on Maui, has a 1.8-m diameter primary mirror with a f/4.4 Cassegrain focus. The telescope uses a wide-field 1.4 gigapixel camera mounted at the Cassegrain focus, consisting of sixty Orthogonal Transfer Array devices, each of which has a detector area of 4846 x 4868 pixels. The 10 micron pixels have a plate scale of 0".26, giving a full field-of-view area of 7.06 square degrees, with an active region of roughly 5 square degrees. Pan-STARRS1 uses the griz filters, which are similar to those of SDSS (Abazajian et al. 2009), with the redder y filter replacing the bluer SDSS u filter. The Pan-STARRS1 photometric system in discussed in detail in (Tonry et al. 2012).

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The ASAS-SN network was expanded in 2017 and now comprises five units located in Hawaii, Chile, Texas, and South Africa. With its current capacity, ASAS-SN observes the entire visible sky every ~20 hours to a depth of \( g \approx 18.5 \) mag, weather permitting. ASAS-SN has proven to be a powerful tool for discovering TDEs, and it has discovered three of the four nearest and brightest TDEs to-date: ASASSN-14ae (Holoien et al. 2014; Brown et al. 2016), ASASSN-14li (Holoien et al. 2016b; Prieto et al. 2016; Romero-Cañizales et al. 2016; Brown et al. 2017a), and ASASSN-15oi (Holoien et al. 2016a, 2018). The three ASAS-SN TDEs have since become some of the most well-studied TDEs, with multiwavelength datasets spanning multiple years.

ASAS-SN processes new images using a fully automatic pipeline that incorporates the ISIS image subtraction package (Alard & Lupton 1998; Alard 2000). After the discovery of PS18kh, a host-galaxy reference image was constructed for each ASAS-SN unit that could observe it. As the transient was still brightening, we only used images obtained at least 35 days before the discovery of PS18kh to ensure that no transient flux was present in the references. These reference images were then used to subtract the host galaxy’s background emission from all science images. Aperture photometry was computed for each host-template subtracted science image using the IRAF apphot package, with the magnitudes being calibrated using multiple stars in the field of the host galaxy with known magnitudes in the AAVSO Photometric All-Sky Survey (APASS; Henden et al. 2015). For some of the pre-discovery epochs when PS18kh was still very faint, we stacked multiple science images in order to improve the signal-to-noise (S/N) of our detections. All ASAS-SN photometry (detections and 3-sigma limits) is presented in Table 3 and shown in Figure 1, with error bars on the X-axis used to denote the date ranges of epochs that were combined.

### 2.4. ATLAS light curve

ATLAS is an ongoing survey project with the primary goal of detecting small (10–140 m) asteroids that are on a collision course with Earth (Tonry et al. 2018). ATLAS uses fully robotic 0.5m f/2 Wright Schmidt telescopes located on the summit of Haleakalā and at Mauna Loa Observatory to monitor the entire sky visible from Hawaii every few days. During normal operations, each telescope obtains four 30-second exposures of 200–250 target fields per night, allowing the two telescopes to cover roughly a quarter of the visible sky each night. The four observations of a given field are typically obtained within less than an hour of each other. ATLAS uses two broad filters for its survey operations, with the ‘cyan’ filter (\( c \)) covering 420–650 nm and the ‘orange’ filter (\( o \)) covering 560–820 nm (Tonry et al. 2018).

### 2.5. Swift Observations

After PS18kh was classified as a TDE candidate, we were awarded 20 epochs of Swift TOO observations of PS18kh between 2018 March 27 and 2018 May 29, after which it became Sun-constrained. The UVOT observations were obtained in the \( V \) (5468 Å), \( B \) (4392 Å), \( U \) (3465 Å), \( UVW1 \) (2600 Å), \( UVW2 \) (2246 Å), and \( UVW2 \) (1928 Å) filters (Poole et al. 2008) for all epochs. As each epoch contained 2 observations in each filter, we first combined the two images in each filter using the HEAsoft software tool uvotimsum,

### Table 3. Host-Subtracted Photometry of PS18kh

<table>
<thead>
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<th>MJD</th>
<th>Filter</th>
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<th>Telescope/Observatory</th>
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<td>PS1</td>
</tr>
<tr>
<td>58225.25</td>
<td>( z )</td>
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</tr>
<tr>
<td>58261.12</td>
<td>( UVW2 )</td>
<td>18.71 ± 0.07</td>
<td>Swift</td>
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<td>18.84 ± 0.07</td>
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<tr>
<td>58267.82</td>
<td>( UVW2 )</td>
<td>18.66 ± 0.07</td>
<td>Swift</td>
</tr>
</tbody>
</table>

**Note:** Host-subtracted magnitudes and 3-sigma upper limits in all photometric filters used for follow-up data. The Telescope/Observatory column indicates the source of the data in each epoch: “PS1”, “ASAS-SN”, and “ATLAS” are used for Pan-STARRS, ASAS-SN, and ATLAS survey data, respectively; “CFHT”, “PO”, and “LT” are used for Canada-France-Hawaii Telescope, Post Observatory, and Liverpool Telescope data, respectively; and “Swift” is used for Swift UVOT data. “Syn” indicates magnitudes synthesized from follow-up spectra, as described in Section 2.7. These measurements are corrected for Galactic extinction, and all magnitudes are presented in the AB system. This Table is published in its entirety in a machine-readable format in the online journal; a portion is shown here for guidance regarding its form and content.
and then extracted counts from the combined images in a 5\arcsec radius region using the software task `uvotsource`, with a sky region of \( \sim 40\arcsec \) radius used to estimate and subtract the sky background. The UVOT count rates were converted into magnitudes and fluxes based on the most recent UVOT calibration (Poole et al. 2008; Breeveld et al. 2010).

We corrected the UVOT magnitudes for Galactic extinction assuming \( R_V = 3.1 \) and \( A_V = 0.128 \) (Schlafly & Finkbeiner 2011), assuming a Cardelli et al. (1989) extinction law. Using the synthetic \( 5\arcsec \) host fluxes calculated from the FAST fits, we then subtracted the host flux from each UVOT observation to isolate the transient flux in each band. To enable direct comparison to ASAS-SN magnitudes and other ground-based follow-up photometry, we converted the UVOT \( B \) - and \( V \)-band data to Johnson \( B \) and \( V \) magnitudes using publicly available color corrections\(^3\). The host-subtracted \textit{Swift} UVOT photometry and 3-sigma limits are presented in Table 3 and are shown in Figure 1.

PS18kh was also observed using the \textit{Swift} XRT. All observations were taken in photon counting mode, and were reprocessed from level one XRT data using the \textit{Swift} XRTPIPELINE version 0.13.2. As suggested in the \textit{Swift} XRT data reduction guide\(^4\), standard filters and screening were applied, along with the most up-to-date calibration files. We used a source region centered on the position of PS18kh with a radius of \( 30'' \), and a source free background region centered at \((\alpha, \delta) = (07:57:07.71, +34:20:59.97)\) with a radius of \( 150'' \). All extracted count rates were corrected for the encircled energy fraction (a \( 30'' \) source radius contains only \( \sim 90\% \) of the counts from a source at 1.5 keV; Moretti et al. 2004).

To increase the signal-to-noise of our observations, we combined the individual XRT observations using XSELECT version 2.4d. We combined our observations into three time-bins spanning the full \textit{Swift} observing campaign and merged all observations together to extract an X-ray spectrum with the highest signal-to-noise possible. From these merged observations, we used the task `XRTPRODUCTS` to extract both source and background spectra. Ancillary response files were derived using `XRTMKARF` and merged exposure maps were created from the individual observations using `XIMAGE` version 4.5.1. We took advantage of the ready-made response matrix files (RMFs), which are obtained from the most up-to-date \textit{Swift} CALDB. The XRT fluxes and 3-sigma upper limits measured from the merged observations are given in Table 4.

The spectral data were analyzed using the X-ray spectral fitting package (XSPEC) version 12.9.1 and \( \chi^2 \) statistics. Each spectrum was grouped using FTOOLS command `grppha` to have a minimum of 10 counts per energy bin. Due to the faintness of the X-ray emission from this source, the signal-to-noise of the resulting spectrum is quite low. As such, the spectrum is insufficient to constrain the column density \( (N_H) \) and so we fixed it to \( N_H = 4.42 \times 10^{20} \) cm\(^{-2} \), which is the Galactic HI column density in the direction of PS18kh (Kalberla et al. 2005).

2.6. Other Photometric Observations

In addition to the survey data and \textit{Swift} observations, we also obtained photometric observations from multiple ground observatories. \( BVgriz \) observations were obtained from the 2-m Liverpool Telescope (Steele et al. 2004) and from the 24-inch Post Observatory robotic telescopes located in Mayhill, New Mexico, and Sierra Remote Observatory in California. Additional \( u \) -band data were obtained with MegaCam (Boulade et al. 1998) on the Canada-France-Hawaii Telescope (CFHT). After flat-field corrections were applied to these follow-up data, we measured \( 5\arcsec \) aperture magnitudes using the IRAF `apphot` package, with the magnitudes calibrated using several stars in the field with well-defined magnitudes in SDSS DR14. \( B \) and \( V \) reference star magnitudes were calculated from the SDSS \( ugriz \) magnitudes using the corrections from Lupton (2005).

As was done with the \textit{Swift} UVOT magnitudes, after calculating the \( 5\arcsec \) aperture fluxes in each image, we corrected for Galactic extinction and subtracted the host flux using the synthetic host magnitudes calculated from the FAST fits. The host-subtracted ground-based follow-up photometry are presented in Table 3 and are shown in Figure 1.

2.7. Spectroscopic Observations

After classifying PS18kh as a TDE candidate, we began a program of spectroscopic follow-up to complement our photometric follow-up. The telescopes and instruments used to obtain follow-up spectra as part of this campaign included:

\begin{table}
\centering
\caption{\textit{Swift} XRT photometry of PS18kh}
\begin{tabular}{ccc}
\hline
MJD Range & Unabsorbed Flux & Uncertainty \\
\hline
58204–58221 & \( 3.44 \times 10^{-14} \) & \( 1.21 \times 10^{-14} \) \\
58223–58240 & \( 3.16 \times 10^{-14} \) & \( 1.21 \times 10^{-14} \) \\
58242–58267 & < \( 2.88 \times 10^{-14} \) & --- \\
\hline
\end{tabular}
\end{table}

\(^3\) https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/swift/docs/uvot/uvot_caldb_coltrans_02b.pdf

\(^4\) https://swift.gsfc.nasa.gov/analysis/xrt_swguide_v1_2.pdf
Figure 1. Host-subtracted UV and optical light curves of PS18kh spanning roughly 2 months before and 2.5 months after peak brightness (MJD=58195.1, measured from the ASAS-SN g light curve; see Section 3.1). Pan-STARRS1 (griz), ASAS-SN (gV), and ATLAS (o) survey data are shown as stars, circles, and diamonds, respectively; follow-up Swift UVOT data are shown as squares; and follow-up ground data from LT (BVgriz), Post Observatory (BVgriz), and CFHT (o) are shown as triangles, pentagons, and right-facing triangles, respectively. Photometry synthesized from spectra are shown as open circles. 3-sigma upper limits are indicated with downward arrows. Error bars in time are used to denote the date range of observations that have been combined to obtain a single measurement. Swift B and V data have been converted to Johnson B and V magnitudes to enable direct comparison with ground-based follow-up data. The blue vertical bar on the X-axis shows the epoch of discovery, and the black bars show epochs of spectroscopic follow-up. All data have been corrected for Galactic extinction and are presented in the AB system.
SNIFS on the University of Hawaii 88-inch telescope, the Inamori-Magellan Areal Camera and Spectrograph (IMACS; Dressler et al. 2011) on the 6.5-m Magellan-Baade telescope, the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) on the 8.2-m Gemini North telescope, the SPectrograph for the Rapid Acquisition of Transients (SPRAT) on the Liverpool Telescope, the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck I 10-m telescope, and the Multi-Object Double Spectrographs (MODS; Pogge et al. 2010) mounted on the dual 8.4-m Large Binocular Telescope (LBT).

We reduced and calibrated the majority of the spectra using IRAF following standard procedures, including bias subtraction, flat-fielding, 1-D spectral extraction, and wavelength calibration by comparison to an arc lamp. The MODS spectra were reduced using the MODS spectroscopic pipeline. The observations were flux calibrated with spectroscopic standard star spectra obtained on the same nights as the science spectra. In some cases, we also performed telluric corrections using the standard star spectra, and in other cases we masked prominent telluric features. In order to increase the signal-to-noise of later observations from SNIFS, spectra taken within 2–3 days of each other were co-added, with each spectrum weighted by its uncertainty. Details of all spectra obtained for PS18kh are presented in Table 7.

We further calibrated the spectra using the photometric measurements. We extracted synthetic photometric magnitudes for each filter that was completely contained in the wavelength range covered by the spectrum and for which we could either interpolate the photometric light curves or extrapolate them by 1 hour or less. We fit a line to the difference between the observed and synthetic flux as a function of central wavelength and scaled each spectrum by this fit. We corrected the observed spectra for Galactic reddening using a Milky Way extinction level by fitting a line to regions on the emission lines. (See Section 3.3.) We first estimated a continuum emission level by fitting a line to regions on the emission lines. (See Section 3.3.) We first estimated a continuum emission level by fitting a line to regions on both sides of the Hα emission feature, subtracting this continuum, and fitting a Gaussian line profile to the Hα emission line. From the Gaussian fit we obtain an estimated redshift of $z = 0.074$. As a sanity check, we also fit the Hβ line from the IMACS spectrum and the Hα line from the 2018 April 01 Gemini GMOS spectrum using the same procedure, obtaining consistent results.

To estimate the time of peak light, we fit a parabolic function to the ASAS-SN $g$ and ATLAS $o$ light curves near peak. In order to estimate the uncertainty on the peak dates, we used a procedure similar to the one used to estimate the uncertainties on the host galaxy parameters: we generated 10000 realizations of the $g$ and $o$ light curves near peak, with each magnitude perturbed by their respective uncertainties and assuming Gaussian errors. We then fit a parabola to each of these light curves and calculated the 68% confidence interval and median $t_\text{peak}$ values. For $g$-band, we obtain $t_{o,\text{peak}} = 58195.1^{+0.8}_{-0.7}$ and $m_{g,\text{peak}} = 17.4$, while for $o$-band we obtain $t_{o,\text{peak}} = 58198.5^{+0.5}_{-0.6}$ and $m_{o,\text{peak}} = 17.6$. This discrepancy between filters is not unexpected, as PS18kh was becoming redder in optical filters, which will result in later peak dates in redder filters. We adopt the median $g$-band peak of $t_{o,\text{peak}} = 58195.1$, corresponding to 2018 March 18.1, when discussing data with respect to peak time throughout the manuscript.

3. ANALYSIS

3.1. Position, Redshift, and $t_\text{peak}$ Measurements

We used the discovery $i$-band image obtained by Pan-STARRS1 on 2018 March 02 and the corresponding Pan-STARRS1 $i$-band reference image to measure an accurate position of the transient. We first measured the centroid position of the transient in the host-subtracted discovery image and the centroid position of the host galaxy nucleus in the reference image using the IRAF task imcentroid, then calculated the offset between the two positions. From this method, we obtain a position of RA=07:56:54.53, Dec=+34:15:43.58 for PS18kh. We calculate an offset of 0.28 ± 0.29 arcseconds from the host nucleus, corresponding to a physical projected distance of 0.45 ± 0.48 kpc at the distance of the host.

To estimate the redshift of the transient, we used the Magellan IMACS spectrum obtained on 2018 March 25, five days after peak, as this spectrum had both high S/N and was obtained before the double-peaked feature started to appear in the emission lines. (See Section 3.3.) We first estimated a continuum emission level by fitting a line to regions on both sides of the Hα emission feature, subtracting this continuum, and fitting a Gaussian line profile to the Hα emission line. From the Gaussian fit we obtain an estimated redshift of $z = 0.074$. As a sanity check, we also fit the Hβ line from the IMACS spectrum and the Hα line from the 2018 April 01 Gemini GMOS spectrum using the same procedure, obtaining consistent results.

http://www.astronomy.ohio-state.edu/MODS/Software/modsIDL/
Figure 2. Spectroscopic evolution of PS18kh spanning from 11 days before peak (2018 March 18) through 64 days after peak. The spectra have been flux-calibrated to the photometry, as described in Section 2.7. Hydrogen and helium emission features common to TDEs are indicated with red dashed lines and telluric bands are shown in light gray. For cases where the telluric features were not removed in calibration, the A-band telluric feature has been masked to facilitate plotting. The spectra labelled “2018/05/12” and “2018/05/19” are coadded spectra from SNIFS, combining data from 2018 May 11−12 and 2018 May 17−19, respectively.
3.2. Light Curve Analysis and SED Fits

The ASAS-SN and ATLAS survey data make PS18kh one of the few TDE candidates with a well-sampled rising light curve. PS18kh brightened by roughly 2.1 magnitudes over 40 days in g-band, reaching a peak of $m_{g,peak} = 17.3$. It brightened by a similar amount in the ATLAS o-band over the same time frame, but the rise is less dramatic in redder filters such as i and z. After peak, PS18kh faded gradually in all optical filters redder than U, but was still brighter than the magnitude of first detection in g-band in the observations obtained 78 days after peak. At i-band, in contrast, the transient was fainter in later data than it was in the discovery epoch, and in some cases was consistent with the measured host magnitude. In the Swift UV+U bands, the flux plateaus, or begins to re-brighten ~ 50 days after peak, with the effect being more pronounced in bluer filters.

To better quantify the physical parameters of the system, we modeled the UV and optical SED of PS18kh for epochs where Swift data were available as a blackbody using Markov Chain Monte Carlo methods, as was done for the previous ASAS-SN TDEs (e.g., Holoien et al. 2014, 2016b; Holoien et al. 2016, 2017a; Brown et al. 2016, 2017a; Holoien et al. 2018). So as not to overly influence the fits, we performed the blackbody fits using a flat prior of $10000 \leq T \leq 55000$ K in all epochs. The blackbody models fit the data well, and the resulting temperature evolution is shown in Figure 3, with time corrected to rest-frame days relative to peak.

The blackbody fits indicate that for the first ~ 45 days after peak, the temperature of PS18kh held relatively constant around $T \approx 14000$ K. This temperature and constant behavior is not uncommon for TDEs (e.g., Holoien et al. 2014, 2016b; Brown et al. 2016, 2017a; Holoien et al. 2018). However, after the UV flux began to rise, the transient became hotter, with the temperature increasing to $T \approx 22000$ K over the following 3 weeks. This is similar to that of other TDEs, but the rising behavior seen ~ 50 days after peak is unusual among TDE candidates. Unfortunately, it is unclear whether the temperature continued to increase further, as PS18kh became Sun-constrained for Swift not long after the source began to rebrighten in the UV.

For those epochs with Swift data, we also estimated the bolometric luminosity of PS18kh from the blackbody fits. In order to better take advantage of the high-cadence light curve, we used the epochs with Swift blackbody fits to calculate bolometric corrections to the g-band data taken within 1 day of the Swift observations, or to g-band magnitudes interpolated between the previous and next g-band observations if there was no observation within 1 day of the Swift observation. We then used these bolometric corrections to estimate the bolometric luminosity of PS18kh from the g-band data for epochs when we did not have Swift data, linearly interpolating the bolometric corrections for each g-band epoch. For epochs prior to our first Swift observation, we used the bolometric correction from the first Swift SED fit. We do not correct the data taken after the last Swift observation, as the g-band continued to decline while the UV was re-brightening, and we do not want to extrapolate a rising or falling behavior beyond what our SED fits can tell us. The luminosity evolution calculated from the Swift SED fits and estimated from the g-band light curve is shown in Figure 4.

As suggested by the Swift light curves, while the luminosity initially drops after peak, it begins to rise again ~ 50 (rest-frame) days after peak. As we did with previous TDEs, we fit the initial fading light curve ($0 < t < 50$ days) with an exponential profile $L = L_0 e^{-(t-t_0)/\tau}$, a $L = L_0(t-t_0)^{-5/3}$ power-law profile, and a power law where the power-law index is fit freely, $L \propto (t-t_0)^{-\alpha}$. Our best fit parameters for each model are as follows: for the exponential profile we obtain $L_0 = 10^{43.9}$ ergs s$^{-1}$, $t_0 = 58184.7$, and $\tau = 50.1$ days; for the $t^{-5/3}$ power law we obtain $L_0 = 10^{46.7}$ ergs s$^{-1}$ and $t_0 = 58142.4$; and for the free power law we obtain $L_0 = 10^{44.5}$ ergs s$^{-1}$, $t_0 = 58190.4$, and $\alpha = 0.62$. We find that both power laws provide better fits than the exponential profile, with $\chi^2 = 28.8$, $\chi^2 = 41.4$, and $\chi^2 = 57.0$, for the free power law, the $t^{-5/3}$ power law, and the exponential fit, respectively. All three fits are shown in Figure 4. A $t^{-0.62}$ power law profile is closest to the $t^{-5/12}$ power law expected for disk-dominated emission (e.g., Auchettl et al. 2017), implying that the emission from PS18kh may not be fallback-dominated as expected from theory.
that the emission we see arises from the TDE, rather than an underlying AGN.

Integrating over the entire rest-frame bolometric light curve calculated from the g-band data and the Swift blackbody fits gives a total radiated energy of $E = (3.82 \pm 0.25) \times 10^{50}$ ergs, with $(1.58 \pm 0.22) \times 10^{50}$ ergs being released during the rise to peak. This shows that a significant fraction of energy emitted by TDEs can be emitted during the rise to peak, and highlights the need for early detection. The total radiated energy corresponds to an accreted mass of $M_{\text{Acc}} \simeq 0.002\eta_{0.1}^{-1} M_\odot$, where the accretion efficiency is $\eta = 0.1\eta_{0.1}$. As with other TDEs, a negligible fraction of the bound stellar material appears to actually accrete onto the black hole, or the material is accreting with a very low radiative efficiency.

### 3.3. Spectroscopic Analysis

The dominant spectral features of PS18kh are a strong blue continuum and broad hydrogen emission lines, similar to the features that have been seen in most TDEs discovered at optical wavelengths (e.g., Arcavi et al. 2014). PS18kh falls into the “hydrogen-rich” group of TDEs, with strong Balmer lines, particularly H$_\alpha$ and H$_\beta$, visible in most epochs, but with weak or absent helium emission features. There is some suggestion of emission that is consistent with He I 5875Å at the redshift of PS18kh, but the He II 4686Å line seen in many TDEs is notably absent.

Our earliest spectroscopic follow-up was obtained prior to or within a few days of the g-band peak, and some interesting trends can be seen in the spectra. In particular, the spectral slope becomes steeper near peak before beginning to slowly flatten again over the course of our observations, which is unsurprising given that the TDE was optically brightest at peak. The emission line features become stronger as time progresses, and only become clearly visible shortly after peak light. Unfortunately our first spectrum, the classification spectrum obtained on 2018 March 7, was taken through clouds, making it difficult to determine whether there were emission lines prior to peak. As was seen with the optical photometry, there is little evidence of the UV re-brightening in the optical spectra—the continuum level remains relatively flat, and the lines show no significant evolution.

The spectra of PS18kh differ from the majority of other TDEs in one respect: the H$_\alpha$, and in some cases H$_\beta$, lines show evidence of an evolving, boxy shape that becomes more prominent over time, and in some later epochs there is a suggestion of double peaks in the H$_\alpha$ profile. A similar double-peak H$_\alpha$ profile was seen in the TDE PTF09djl, though in that case, the peaks showed a much larger separation (Arcavi et al. 2014; Liu et al. 2017a).

The possibility that TDEs could lead to the formation of line-emitting (elliptical) disks was discussed by Eracleous et al. 2014; Liu et al. 2017a).
et al. (1995) and Guillochon et al. (2014). In the cases of two recent TDEs, PTF09djil and ASASSN-14li, an elliptical disk model has been used to fit the emission line profiles and model the properties of the accretion disk (Liu et al. 2017a; Cao et al. 2018). Here we use similar models to infer the properties of the accretion disk, and potentially the stellar debris, of PS18kh.

We consider models for the profiles of the broad Hα emission lines that attribute the emission to a thin, photoionized “skin” on the surface of a relativistic, Keplerian disk. Our approach is motivated by the success of such models in describing the Balmer line profiles of active galaxies and quasars in general (e.g., Popović et al. 2004; Bon et al. 2009; La Mura et al. 2009; Storchi-Bergmann et al. 2017) and recent theoretical scenarios that associate the broad-line region with the accretion disk in quasars and active galaxies (e.g., Elitzur et al. 2014), as well as the studies of PTF09djil and ASASSN-14li mentioned above.

The model line profiles are obtained in the observer’s frame by adopting the formalism detailed in Chen et al. (1989), Chen & Halpern (1989), Eracleous et al. (1995), and Flohic et al. (2012) by computing the integral

\[
f_\nu \propto \int d\varphi \int \xi d\xi \, L_\nu(\xi, \varphi, r_g) D^3(\xi, \varphi) \Psi(\xi, \varphi),
\]

over the surface of the disk. The functions in the integrand are expressed in polar coordinates in the frame of the disk where \( \varphi \) is the azimuthal angle in the plane of the disk, \( r_g/r_e \) is the dimensionless radial coordinate, \( r_g \equiv GM_*/c^2 \) is the gravitational radius, and \( M_* \) is the mass of the black hole. The axis of the disk makes an angle \( i \) with the line of sight to the observer (the “inclination” angle) and the line-emitting portion of the disk is enclosed between radii \( \xi^m_{\text{disk}} \) and \( \xi^o_{\text{disk}} \) (see Fig. 1 of Chen et al. 1989).

The functions \( D \) and \( \Psi \) describe the gravitational and transverse redshifts and light bending, respectively, in the weak-field approximation. The function \( L_\nu \) represents the apparent emissivity of the disk and includes terms that account for the intrinsic brightness distribution of the disk, the (potentially anisotropic) escape probability of line photons in the direction of the observer, and local line broadening (see equation 2 of Flohic et al. 2012, and the associated discussion). The local profile of the line is assumed to be a Gaussian of standard deviation \( \sigma \) that includes contributions from local turbulence, electron scattering, and blurring resulting from the finite cells used in the numerical integration. The intrinsic brightness profile of the disk is parameterized by a power-law of the form \( \xi^{-q} \) where \( q \) takes values between 1 and 3, motivated by the results of photoionization calculations by Dumont & Collin-Souffrin (1990a,b). This axisymmetric emissivity pattern can be perturbed either by making the disk elliptical or by superposing a logarithmic spiral, as we explain below.

At early times, the observed profile of the Hα line in PS18kh appears bell-shaped and somewhat asymmetric with an extended red wing. At late times, the profile evolves to a flat-topped or, sometimes, double-peaked shape. It maintains its red wing and it sometimes shows a blue shoulder. We
interpret this sequence of line profiles as indicating a progressive decline in the optical depth of the line emitting skin of the disk. This interpretation is motivated by the behavior of the theoretical line profiles with optical depth and by the expected evolution of the accretion rate through the disk and onto the black hole. At early times the high accretion rate is likely to lead to the emission of a wind from the surface of the accretion disk, consisting of stellar debris from the disruption, whose dense base layers will provide a substantial optical depth to the line photons. As the accretion rate drops and the debris moves outward from the black hole, the density of the wind and the optical depth of the line-emitting skin of the disk decline accordingly. We also note that the blue shoulder in the observed late-time Hα profiles cannot be reproduced by a model of an axisymmetric disk. Therefore, we postulate that a non-axisymmetric perturbation is present and we explore whether an elliptical disk or a disk with a spiral arm can describe this perturbation successfully.

The spectra obtained prior to 2018 March 25 are consistent with little-to-no Hα emission, indicating the optical depth of the material surrounding the accretion disk is too large to obtain a model fit to the data. To represent the observed early-time Hα profiles (those between 2018 March 25 and 2018 April 1) we adopt the wind model discussed by Murray et al. (1995, see also Flohic et al. 2012, Chiang & Murray 1996, Murray & Chiang 1997, and Chajet & Hall 2013). In these models, the apparent brightness profile of the disk is non-axisymmetric, as shown, for example, in Figure 4 of Flohic et al. (2012), because of the anisotropic escape probability of photons through the emission layer. The resulting line profiles have round or somewhat flat tops and an extended red wing because of relativistic effects (see examples in Fig. 5 of Flohic et al. 2012). The free parameters of the model are the inner and outer radii of the line-emitting portion of the disk, ξ_{in} and ξ_{out}, the local line width, σ (in km s^{-1}), the emissivity power-law index, q, the disk inclination angle, i, the angle of the wind streamlines relative to the plane of the disk, λ (see Fig. 1 of Murray & Chiang 1997), and the normalization of the position-dependent optical depth pattern, given in terms of τ, the optical depth in the direction of the observer at a fiducial position in the disk of (ξ, ϕ) = (1000, 0).6

To fit the profiles at late times, we tried two different models, an elliptical disk (see Eracleous et al. 1995), and a circular disk with a single spiral arm (see Gilbert et al. 1999; Storchi-Bergmann et al. 2003). In both models the optical depth of the emission layer is negligible although we do experiment with a model that combines a spiral arm and a finite optical depth to fit the 2018 April 1 model. Figure 5 shows illustrations of the two models, which are described in more detail below.

**Elliptical Disk.** –: The disk streamlines are nested ellipses of constant eccentricity and aligned semi-major axes. There are two more free parameters in addition to those noted above, the eccentricity and orientation of the semi-major axis relative to the observer, e and ϕ_0. A model of this type was considered by Guillouchen et al. (2014) in their discussion of the evolution of the tidal disruption event PS1-10jh and applied to PTF09djl and ASASSN-14li by Liu et al. (2017a) and Cao et al. (2018).

**Disk With Spiral Arm.** –: The axisymmetric eccentricity of a circular disk is perturbed by a logarithmic spiral, as described in equation (2) of Storchi-Bergmann et al. (2003). In addition to the five free parameters that describe a circular disk, there are five free parameters that describe the spiral pattern: the pitch angle, width, and azimuth of the spiral arm at the inner disk, p, w, and ϕ_m, respectively, its brightness contrast relative to the underlying axisymmetric disk, A, and its outer radius, ξ_{out} (its inner radius is the same as the inner radius of the line emitting portion of the disk, i.e., ξ_{spiral} = ξ_{disk}).

While a complete exploration of the model parameter space is beyond the scope of this work, we embark on a qualitative exploration where the goodness of all fits was assessed by eye. We first fitted the 2018 March 25 spectrum with a wind model and then adjusted the optical depth and disk radii to reproduce the March 30, March 31, and April 1 spectra.

### Table 5. Fixed Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Underlying Disk</strong></td>
<td></td>
</tr>
<tr>
<td>q</td>
<td>2.2</td>
</tr>
<tr>
<td>i</td>
<td>65 degrees</td>
</tr>
<tr>
<td>σ</td>
<td>800 km s^{-1}</td>
</tr>
<tr>
<td><strong>Wind</strong></td>
<td></td>
</tr>
<tr>
<td>λ</td>
<td>10 degrees</td>
</tr>
<tr>
<td>η</td>
<td>0</td>
</tr>
<tr>
<td><strong>Spiral Arm</strong></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>2</td>
</tr>
<tr>
<td>p</td>
<td>10 degrees</td>
</tr>
<tr>
<td>w</td>
<td>80 degrees</td>
</tr>
</tbody>
</table>

*Note—Fixed parameters for the disk+wind+spiral arm model, as defined in §3.3 of the text. The values listed in this table do not change with time. The parameters that do change with time are given in Table 6.*

---

6 In the current implementation of this model we do not allow the optical depth normalization to vary with radius; in the notation of Flohic et al. (2012) we set η = 0.
Figure 6. Evolution of the Hα profile of PS18kh. A linear estimate of the continuum emission was subtracted from each epoch and the date of each spectrum is shown in the upper-left corner of each panel. The cyan lines show disk+wind model fits to the spectra taken between 2018 March 25 and 2018 April 1, the magenta line shows an elliptical disk model fit to the 2018 April 1 spectrum, and the red line shows a disk+spiral arm model fit to the 2018 April 1 and later spectra. The model shown in all epochs after 2018 April 1 is the same model, which has been scaled by a factor of 1.15−1.8 and blueshifted by 15−25Å to fit the line profiles. All models shown are described in Section 3.3. The spectra from 2018 April 1 and 2018 May 10 have prominent telluric water vapor absorption bands in the red wing of the line (6700–6800 Å) that have not been corrected.
We then fitted the 2018 April 25 spectrum with a disk and spiral model and an elliptical disk model and compared that model with the other observed spectra obtained after 2018 April 1 to check whether the could adequately describe those spectra as well. We estimated the uncertainties in the model parameters by perturbing them about their best-fit values and adjusting the other parameters to get a good fit until no good fit was possible. Thus, we find that the inclination angle can be determined to approximately ±5°, the inner disk radius to ±50r_g, the outer radius to ±2000r_g, the emissivity power law index to ±0.2 and the broadening parameter to ±300 km s^{-1}. The wind optical depth could be determined to a factor of 3 while the wind opening angle was held fixed at 10° based on the physical considerations discussed in Murray & Chiang (1997). The orientation of the spiral pattern could be determined to ±20°, its pitch angle to ±5°, its angular width to ±20°, its outer radius to ±2000r_g, and its contrast to ±1. The eccentricity of the elliptical disk could be determined to ±0.2 and the orientation of its major axis to ±10°. The best-fit parameters for the disk+wind+spiral arm models are given in Table 5 and Table 6.

![Figure 7. Evolution of the Hα (red squares) and Hβ (blue circles) luminosities of PS18kh. Errorbars show 30% errors on the line fluxes. The black line shows the Hα emission that would be expected from case B recombination, given the Hβ emission.](image)

Table 6. Variable Parameters for Line Models

<table>
<thead>
<tr>
<th>Date</th>
<th>τ</th>
<th>ξ_{disk}</th>
<th>ξ_{spiral}</th>
<th>φ_{win} (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/25</td>
<td>2.10</td>
<td>250−10000</td>
<td>no spiral arm</td>
<td>...</td>
</tr>
<tr>
<td>3/30</td>
<td>3.18</td>
<td>400−10000</td>
<td>no spiral arm</td>
<td>...</td>
</tr>
<tr>
<td>3/31</td>
<td>1.25</td>
<td>500−15000</td>
<td>500−5500</td>
<td>40</td>
</tr>
<tr>
<td>4/01</td>
<td>0.38</td>
<td>500−20000</td>
<td>500−9000</td>
<td>81</td>
</tr>
<tr>
<td>4/11 and later</td>
<td>&lt; 0.02</td>
<td>500−15000</td>
<td>500−20000</td>
<td>40</td>
</tr>
</tbody>
</table>

Note—Parameters for the disk+wind+spiral model used to model the Hα emission line profile that change with time. All optical depths are in the direction of the observer at R = 1000r_g and φ = 0. Radii are inner and outer radii of the disk and the inner and outer radii of the spiral arm in the disk. The angle φ_{win} is the azimuth of the spiral arm at the inner radius of the disk.

As described above, the profiles between 25 March 2018 and 1 April 2018 are well-fit by a disk+wind model, shown with a cyan line in the Figure. As the optical depth of the wind/stellar debris drops, the emission from the underlying disk becomes apparent. We show three fits to the 1 April 2018 spectrum, a disk+wind model, an elliptical disk model (shown in magenta), and a disk with spiral arm model (shown in red). The disk+wind model better reproduces the peak of the line, but underestimates the emission in the wings. The epochs after 2018 April 1 are well-fit by a disk with spiral arm model, with the parameters described in Table 5. Each of the later epochs has been fit with the same model, with the only difference between epochs being a flux scaling factor ranging from 1.15−1.8 and a blueshift ranging from 15−25Å. The flux scaling factor increases with time until 15 May 2018 after which it begins to fall again, while there is no discernible trend in the blueshift. The changing scaling factor and blueshift, as well as small changes in the peak and wings of the emission line from epoch-to-epoch, are likely due to short-term variability in the disk structure on spatial scales too small to properly capture with the models used here.

Taken as a whole, the evolution of the Hα profile in PS18kh shows that as the TDE is brightening towards its peak, the disk is obscured by optically thick material, likely debris from the disruption. Between 2018 March 25 and 2018 April 1, this material becomes progressively more optically thin while the line-emitting portion of the disk grows in size, and the emission lines are well-fit by a disk+wind model. After 2018 April 1, the emission from the disk is clearly seen, and the double-peaked/boxy profile is well-fit by a disk with a spiral arm model. The scale of the disk is similar to that seen in PTF09ge and ASASSN-14li (Liu et al. 2017a; Cao et al. 2018), indicating that this is likely a common feature of TDEs. The disk has non-axisymmetric perturbations that are approximated by the spiral arm. Slight variation in the scaling of the models to the line profiles after 2018 April 1 suggests that the perturbations are changing with time.

We also measured the luminosities of the Hα and Hβ emission lines from our follow-up spectra for all epochs where the
Figure 8. Left Panel: Luminosity evolution of PS18kh compared to that of the TDEs ASASSN-14ae (cyan squares; Holoien et al. 2014), ASASSN-14li (cyan pentagons; Holoien et al. 2016b), ASASSN-15oi (cyan diamonds; Holoien et al. 2016a), and iPTF16fnl (cyan triangles; Brown et al. 2017b), the hydrogen-rich superluminous supernovae SN 2008es (red squares; Miller et al. 2009; Gezari et al. 2009), SN 2013hx (red triangles; Inserra et al. 2018), and PS15br (red pentagons; Inserra et al. 2018), and the extremely luminous transient ASASSN-15lh (magenta diamonds; Dong et al. 2016; Godoy-Rivera et al. 2017). The full luminosity curve, including both the luminosities calculated from blackbody fits to the Swift data and the luminosities estimated from the g-band light curve, is shown for PS18kh. Time is shown in rest-frame days relative to peak for those objects which have observations spanning the peak of the light curve (PS18kh, SN 2008es, SN 2013hx, PS15br, and ASASSN-15lh) and in days relative to discovery for those objects which do not (ASASSN-14ae, ASASSN-14li, ASASSN-15oi, and iPTF16fnl). Right Panel: The luminosity evolution of PS18kh scaled by a factor of 24.5 and shifted by 15 days compared with that of ASASSN-15lh. These are the only two objects in the sample to exhibit a re-brightening in their UV light curves.

Figure 7 also shows the Hα emission that would be expected given the measured Hβ emission, assuming the emission is driven by case B recombination. The Hα/Hβ ratio is largely consistent with what would be expected from recombination, within noise, similar to what was seen in ASASSN-14li (Holoien et al. 2016b). This also indicates there is little additional extinction from the host galaxy. The measured luminosities for both lines are given in Table 8.

4. DISCUSSION

The temperature, luminosity, radius and spectroscopic evolution of PS18kh are all consistent with other TDEs. However, many of these features are also common to type II superluminous supernovae (SLSNe II), and some of the observational characteristics of PS18kh (e.g., the UV re-brightening and the double-peaked line profiles) are not common to most (or any) other TDEs. In this Section we compare its luminosity, temperature, radius, and spectroscopic evolution to those of TDEs and SLSNe in literature to further investigate the nature of PS18kh.

Our sample of comparison objects includes the TDEs ASASSN-14ae (Holoien et al. 2014), ASASSN-14li (Holoien et al. 2016b), ASASSN-15oi (Holoien et al. 2016a), and iPTF16fnl (Brown et al. 2017b), and the supernovae SN 2008es (Miller et al. 2009; Gezari et al. 2009), SN 2013hx (Inserra et al. 2018), and PS15br (Inserra et al. 2018). The SN sample was chosen because these are the only three
SLSNe that show both a broad Hα feature and no signs of strong interaction between fast moving ejecta and circumstellar shells in their early spectra (Inserra et al. 2018), making them spectroscopically similar to PS18kh. Also included in our comparison sample is ASASSN-15lh, an extremely luminous transient whose nature has been debated, but which is likely either the most luminous SLSN ever discovered (Dong et al. 2016; Godoy-Rivera et al. 2017) or an extreme TDE around a maximally spinning black hole (Leloudas et al. 2016). ASASSN-15lh also exhibited a UV re-brightening, similar to PS18kh (Godoy-Rivera et al. 2017), making it an interesting comparison object.

The left panel of Figure 8 shows the rest-frame luminosity evolution of PS18kh and the transients in our comparison sample, with TDEs and SNe differentiated by color. The TDE sample has peak luminosities in the range $10^{9.8} L_\odot \lesssim L \lesssim 10^{10.8} L_\odot$ while the SN sample ranges from $10^{10} L_\odot \lesssim L \lesssim 10^{10.8} L_\odot$, meaning the luminosity of PS18kh is consistent with both types of object. ASASSN-15lh is clearly an outlier in peak luminosity from all the other objects in the sample, including PS18kh. While none of the TDEs in the sample were discovered prior to peak, preventing a comparison of the rising phase of the light curve, the rise time of PS18kh seems to be roughly consistent with that of the SNe in the sample.

To examine the similarity of the re-brightening seen in the light curves of PS18kh and ASASSN-15lh, we scaled the peak luminosity of PS18kh by a factor of 24.5 to match the peak of ASASSN-15lh, and shifted the light curve of PS18kh by 15 rest-frame days so that the peak of the PS18kh light curve aligns with the highest measured luminosity of ASASSN-15lh. The resulting comparison is shown in the right panel of Figure 8. PS18kh rises a bit more steeply than ASASSN-15lh does, but after peak the rate of decline is very similar between the two objects. PS18kh begins to re-brighten sooner, with the rise beginning at $t \approx 59$ rest-frame days, while ASASSN-15lh begins to re-brighten at $t \approx 73$ rest-frame days, but the shape of the two light curves is very similar. Assuming PS18kh is a TDE, this perhaps lends credence to the interpretation that ASASSN-15lh was the result of a TDE. However, the two objects differ in other respects, such as their temperature and radius evolution and their spectroscopic features (see Figures 9, 10, and 11), which indicates that the physical mechanisms responsible for the re-brightening likely differ between the two transients.

Figure 9 shows the evolution of the temperature measured from the blackbody fits to the Swift observations of PS18kh compared to the temperature evolution of the other objects in our comparison sample. All three hydrogen-rich SLSNe show a very similar temperature evolution, with the temperature declining steadily from a peak of $T \sim 10000$ K, while the TDEs all show either rising or constant temperature evolution, with temperatures in the range of $10000 \lesssim T \lesssim 50000$ K. ASASSN-15lh is clearly something different from the other objects, showing both a decline similar in shape to that of the hydrogen-rich SLSNe, and a later rise similar to that of the TDEs. The temperature evolution of PS18kh very strongly resembles that of ASASSN-14ae in both shape and magnitude, including a rising temperature after $t \sim 40$ days. This evolution strongly differentiates it from the SLSN sample and from ASASSN-15lh.

Figure 10 shows the evolution of the radius measured from the blackbody fits to the Swift observations of PS18kh compared to the radius evolution of the other objects in our comparison sample. All three hydrogen-rich SLSNe and ASASSN-15lh stand out very clearly from the TDEs and PS18kh. While the SNe show larger and relatively constant photospheric radii, all the TDEs show a declining radius. PS18kh again very closely resembles ASASSN-14ae in both shape and magnitude, and is clearly differentiated from the SLSN sample and ASASSN-15lh.

Finally, in Figure 11 we compare spectra of PS18kh to those of ASASSN-14ae, SN 2013hx, and ASASSN-15oi at two similar rest-frame phases (near peak/discovery and roughly 40 days after peak/discovery). In the early epoch, the spectra of PS18kh resembles both that of ASASSN-14ae and that of SN 2013hx, with a broad Hα emission feature and strong, blue, relatively featureless continuum. However, the later epoch clearly differentiates PS18kh from the SLSN, as both ASASSN-14ae and PS18kh continue to ex-
Figure 10. Radius evolution of PS18kh taken from blackbody fits to epochs with Swift observations compared with the temperature evolution of the objects in our comparison sample. Symbols and colors match those of Figure 8 and all times are plotted in days relative to peak or discovery, as outlined in the caption of Figure 8. The left scale shows the radius in units of cm, while the right scale gives the corresponding radius in units of the gravitational radius for a $10^7 M_\odot$ black hole.

Habit fairly strong continuum emission and broad hydrogen emission features, while the continuum shape of the spectra of SN 2013hx has started to change, reflecting its cooling temperature, and a number of absorption features have appeared. The spectra of ASASSN-15oi show almost no evolution at all between the two epochs, as it exhibits very blue spectra with broad absorption features at bluer wavelengths and no emission features, and it is clearly differentiated from the other three objects.

These comparisons show that luminosity evolution does not differentiate between SLSNe and TDEs at early times—while SLSNe tend to be more luminous, objects from both the TDE and SLSN samples show similar peak luminosities and decline rates. Conversely, TDEs and SLSNe quickly differentiate themselves in their temperature, radius, and spectroscopic evolution. SLSNe have smoothly declining temperatures, growing or relatively constant photospheric radii, and absorption features emerge in the spectra over time. TDEs exhibit constant or rising temperatures, shrinking photospheres, and consistently blue spectra with broad hydrogen and helium emission features. ASASSN-15lh is an outlier from both comparison groups in some respects, although its radius evolution very closely matches the SLSN sample. While the shape of its luminosity evolution curve is somewhat similar to that of PS18kh, it is more luminous than any other object in the sample, it has a unique temperature evolution, and its spectra show little-to-no evolution between peak light and $\sim 40$ days after peak light, with no evidence of the broad hydrogen emission features seen in the other objects’ spectra.

It is clear from these comparisons that despite the uniqueness of its light curve shape and the double-peaked line profiles, PS18kh bears a strong resemblance to other known TDEs, and this is the most likely origin for the emission we see during the outburst. Our early survey observations allow us to see the rise to peak light in multiple bands and to estimate its luminosity prior to peak, where we see that a significant fraction of the total early radiated energy is emitted during the rise to peak. UV observations obtained prior to peak will allow us to fit the blackbody SED and better quantify the fraction of energy emitted early for future TDE discoveries.

PS18kh is the third TDE, after PTF09ge and ASASSN-14li (Arcavi et al. 2014; Liu et al. 2017a; Cao et al. 2018), to exhibit emission lines that can be fit by an elliptical disk model, and the first to have spectroscopic coverage prior to and throughout the peak of the light curve. Our modeling allows us to see the likely origin of the broad emission features that are ubiquitous in optically discovered TDEs, and to develop a physical picture for how these lines form in the early stages after the star is disrupted. Similarly detailed datasets will allow us to perform similar analysis on future TDEs, and will be able to tell us whether the model parameters seen in PS18kh are common to all TDEs, or whether there is a range of physical properties that can produce the observations we see. Real-time, high-cadence sky surveys like Pan-STARRS, ASAS-SN, and ATLAS will be able to provide early detection and long-term monitoring of future TDEs, providing us with a population of objects to study to further develop our physical understanding of these highly energetic events.

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\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
\textbf{Object} & \textbf{Peak Luminosity} & \textbf{Radius Evolution} & \textbf{Temperature Evolution} & \textbf{Emission Features} \\
\hline
PS18kh & High & Smooth & Rising & Broad &
\hline
PTF09ge & Low & Smooth & Falling & Narrow &
\hline
ASASSN-14li & Medium & Smooth & Stable & Narrow &
\hline
\end{tabular}
\caption{Comparison of TDEs with respect to luminosity, radius, temperature, and emission features.}
\end{table}
Figure 11. Left Panel: Spectra of PS18kh (black), ASASSN-14ae (red; Holoien et al. 2016b), ASASSN-15lh (blue; Dong et al. 2016), and SN 2013hx (green; Inserra et al. 2018) taken at similar phase shortly after rest-frame peak. (Phase for ASASSN-14ae is in days relative to discovery, as it was discovered after peak light.) Spectra have been offset for clarity and the phase is indicated to the right of each spectrum. Right Panel: Spectra of the same four objects taken 37–39 days after rest-frame peak/discovery.

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Based on data acquired using the Large Binocular Telescope (LBT). The LBT is an international collaboration among institutions in the United States, Italy, and Germany. LBT Corporation partners are: The University of Arizona on behalf of the Arizona university system; Istituto Nazionale di Astrofisica, Italy; LBT Beteiligungsgesellschaft, Germany, representing the Max-Planck Society, the Astrophysical Institute Potsdam, and Heidelberg University; The Ohio State University, and The Research Corporation, on behalf of The University of Notre Dame, University of Minnesota and University of Virginia.

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The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

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### Table 7. Spectroscopic Observations of PS18kh

<table>
<thead>
<tr>
<th>Date</th>
<th>Telescope</th>
<th>Instrument</th>
<th>Exposure Time</th>
</tr>
</thead>
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<tr>
<td>2018 March 07</td>
<td>University of Hawaii 88-inch</td>
<td>SNIFS</td>
<td>1x1200s</td>
</tr>
<tr>
<td>2018 March 18</td>
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<td>1x2000s</td>
</tr>
<tr>
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<td>FAST</td>
<td>1x1800s</td>
</tr>
<tr>
<td>2018 March 20</td>
<td>du Pont 100-inch</td>
<td>WFCCD</td>
<td>2x1200s, 1x900s</td>
</tr>
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<td>2018 March 25</td>
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<td>IMACS</td>
<td>1x1200s</td>
</tr>
<tr>
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<td>3x1800s</td>
</tr>
<tr>
<td>2018 April 01</td>
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<td>GMOS</td>
<td>1x900s</td>
</tr>
<tr>
<td>2018 April 06</td>
<td>Liverpool Telescope 2-m</td>
<td>SPRAT</td>
<td>1x900s</td>
</tr>
<tr>
<td>2018 April 07</td>
<td>Liverpool Telescope 2-m</td>
<td>SPRAT</td>
<td>2x900s</td>
</tr>
<tr>
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<td>Gemini North 8.2-m</td>
<td>GMOS</td>
<td>1x900s</td>
</tr>
<tr>
<td>2018 April 13</td>
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<td>SPRAT</td>
<td>2x900s</td>
</tr>
<tr>
<td>2018 April 13</td>
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<td>SPRAT</td>
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<td>3x1200s</td>
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**NOTE**—Date, telescope, instrument, and exposure time for each of the spectroscopic observations obtained of PS18kh for the initial classification of the transient and as part of our follow-up campaign.
Table 8. Measured H$\alpha$ and H$\beta$ line luminosities

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<th>Rest-Frame Days Relative to Peak</th>
<th>H$\alpha$ Luminosity</th>
<th>H$\beta$ Luminosity</th>
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<td>-0.09</td>
<td>(1.16 ± 0.35)$\times 10^{41}$</td>
<td>—</td>
</tr>
<tr>
<td>1.77</td>
<td>(1.45 ± 0.43)$\times 10^{41}$</td>
<td>—</td>
</tr>
<tr>
<td>1.77</td>
<td>(0.84 ± 0.25)$\times 10^{41}$</td>
<td>—</td>
</tr>
<tr>
<td>6.42</td>
<td>(3.23 ± 0.97)$\times 10^{41}$</td>
<td>(1.59 ± 0.48)$\times 10^{41}$</td>
</tr>
<tr>
<td>11.08</td>
<td>(3.56 ± 1.07)$\times 10^{41}$</td>
<td>(2.74 ± 0.82)$\times 10^{41}$</td>
</tr>
<tr>
<td>12.01</td>
<td>(2.92 ± 0.88)$\times 10^{41}$</td>
<td>(3.65 ± 1.10)$\times 10^{41}$</td>
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<tr>
<td>12.94</td>
<td>(3.34 ± 1.00)$\times 10^{41}$</td>
<td>(1.27 ± 0.38)$\times 10^{41}$</td>
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<tr>
<td>18.53</td>
<td>(3.51 ± 1.05)$\times 10^{41}$</td>
<td>(1.31 ± 0.39)$\times 10^{41}$</td>
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<tr>
<td>22.25</td>
<td>(5.80 ± 1.74)$\times 10^{41}$</td>
<td>(1.08 ± 0.33)$\times 10^{41}$</td>
</tr>
<tr>
<td>24.12</td>
<td>(4.86 ± 1.46)$\times 10^{41}$</td>
<td>(1.36 ± 0.41)$\times 10^{41}$</td>
</tr>
<tr>
<td>24.12</td>
<td>(5.38 ± 1.62)$\times 10^{41}$</td>
<td>(2.06 ± 0.62)$\times 10^{41}$</td>
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<td>26.91</td>
<td>(3.94 ± 1.18)$\times 10^{41}$</td>
<td>(1.65 ± 0.50)$\times 10^{41}$</td>
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<td>35.29</td>
<td>(6.84 ± 2.05)$\times 10^{41}$</td>
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<td>59.50</td>
<td>(4.30 ± 1.29)$\times 10^{41}$</td>
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</tbody>
</table>

Note—H$\alpha$ and H$\beta$ line luminosities measured from the follow-up spectra of PS18kh. In some epochs H$\beta$ was not measurable. The uncertainties shown are 30% uncertainties on the measured fluxes.