X-Ray Brightening and UV Fading of Tidal Disruption Event ASASSN-15oi

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Abstract

We present late-time observations by Swift and XMM-Newton of the tidal disruption event (TDE) ASASSN-15oi that reveal that the source brightened in the X-rays by a factor of ~10 one year after its discovery, while it faded in the UV/optical by a factor of ~100. The XMM-Newton observations measure a soft X-ray blackbody component with $kT_{bb} \sim 45$ eV, corresponding to radiation from several gravitational radii of a central $\sim 10^8 M_\odot$ black hole. The last Swift epoch taken almost 600 days after discovery shows that the X-ray source has faded back to its levels during the UV/optical peak. The timescale of the X-ray brightening suggests that the X-ray emission could be coming from delayed accretion through a newly forming debris disk and that the prompt UV/optical emission is from the prior circularization of the disk through stream–stream collisions. The lack of spectral evolution during the X-ray brightening disfavors ionization breakout of a TDE “veiled” by obscuring material. This is the first time a TDE has been shown to have a delayed peak in soft X-rays relative to the UV/optical peak, which may be the first clear signature of the real-time assembly of a nascent accretion disk, and provides strong evidence for the origin of the UV/optical emission from circularization, as opposed to reprocessed emission of accretion radiation.

Key words: accretion, accretion disks – black hole physics – galaxies: nuclei

1. Introduction

The tidal disruption of a star by a central supermassive black hole (SMBH) is expected to result in a flare of radiation from the accretion of the bound debris via a newly formed accretion disk (Rees 1988; Ulmer 1999). The characteristic temperature of a circularized disk of stellar debris accreting onto an SMBH with $R_{\text{disk}} = 2 R_T$ (as expected from angular momentum conservation) is $T_{\text{max}} = 4.2 \times 10^5 K M_6^{-1/4}$ or $kT_{\text{max}} = 36 eV M_6^{-1/4}$ (Miller 2015), where $M_6 = M_{\text{BH}}/(10^6 M_\odot)$ and $R_T \sim R_\odot (M_{\text{BH}}/M_\odot)^{1/3}$ is the tidal disruption radius. This temperature corresponds to a spectral peak in the soft X-rays at $\sim 0.2$ keV.

Indeed, the first candidates for tidal disruption events (TDEs) were discovered in the soft X-ray (0.1–2.4 keV) band by the ROSAT All-Sky Survey. ROSAT detected luminous X-ray outbursts from several apparently inactive galaxies whose extremely soft spectra, dramatic fading on the timescale of years and a rate of $\approx 10^{-4}$ per year per galaxy were consistent with the theoretical expectations for TDEs (Donley et al. 2002; Komossa 2002). Several more soft X-ray candidates were subsequently discovered with the XMM-Newton Slew Survey and in searches of archival Chandra data (Esquej et al. 2008; Maksym et al. 2010; Saxton et al. 2017), with a range of blackbody temperatures ($kT_{bb} = 0.04–0.12$ keV).

However, dedicated searches with wide-field UV and optical surveys have found a population of candidate TDEs with surprisingly low blackbody temperatures on the order of $(1–3) \times 10^4 K$ (Gezari et al. 2009, 2012; van Velzen et al. 2011; Arcavi et al. 2014; Holoien et al. 2014, 2016a, 2016b; Blagorodnova et al. 2017; Hung et al. 2017), at odds with the basic predictions of radiation from a newly formed accretion disk in a TDE. These lower temperatures have been attributed to larger radii associated with a reprocessing layer (Loeb & Ulmer 1997; Guillochon et al. 2014; Roth et al. 2016), potentially formed from a radiatively driven wind (Miller et al. 2015; Strubbe & Murray 2015; Metzger & Stone 2016) or radiation from stream–stream collisions in the circularizing debris disk itself (Lodato et al. 2012; Piran et al. 2015; Shioikawa et al. 2015; Jiang et al. 2016; Kroll et al. 2016; Bonnerot et al. 2017; Wevers et al. 2017).

Another surprise has been the X-ray weakness of these TDEs discovered in the UV and optical surveys. Only a few optical TDE candidates have been detected with X-ray emission in follow-up observations: GALEX D1-9 and GALEX D3-13 (Gezari et al. 2008); ASASSN-14li (Holoien et al. 2016b); and ASASSN-15oi (Holoien et al. 2016a), with upper limits in a few cases: PS1-10jh (Gezari et al. 2012), iPTF16fnl (Blagorodnova et al. 2017; Brown et al. 2018), and iPTF16axa (Hung et al. 2017).

ASASSN-15oi is a TDE reported by Holoien et al. (2016a) that was discovered by the ASAS-SN survey (Shappee et al. 2014) on 2015 August 14 in the nucleus of a quiescent early-type galaxy at $z = 0.0484$ ($d_L=216$ Mpc for $H_0=69.6$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.29$, $\Omega_\lambda = 0.71$). It was notable for its significant temperature evolution in the first two months after discovery, increasing from $2 \times 10^4 K$ to $4 \times 10^4 K$ and a relatively faint soft X-ray flux. Otherwise, its peak luminosity ($L \sim 1.3 \times 10^{44}$ erg s$^{-1}$), the power-law decay of its light curve, and the He-dominated optical spectrum were similar to other optically discovered TDEs. Here, we report the late-time X-ray brightening of the TDE ASASSN-15oi and show that these observations are consistent with the delayed onset of accretion. This indicates that the optical/UV emission in this TDE (and perhaps by association others) is due to circularization of the debris, rather than reprocessed accretion radiation, as suggested by Piran et al. (2015). The Letter is organized as follows. We present the new observations by Swift and XMM-Newton in Section 2.2, the
evolution of the X-ray spectrum and UV and X-ray light curves up to 600 days after discovery in Section 3, and a comparison of the relevant timescales of a TDE to the timescale of the dramatic evolution in the UV-to-X-ray ratio observed in ASASSN-15oi and our conclusions for the nature of the X-ray and UV/optical components in Sections 4 and 5.

2. Observations

2.1. Swift Observations

ASASSN-15oi was monitored with Swift for \(~40\) epochs in all six UVOT filters; UVW2 (1928 Å), UVM2 (2246 Å), UVW1 (2600 Å), U (3465 Å), B (4392 Å), and V (5468 Å) between 2015 August 27 and 2016 July 24 with a typical exposure time of \(~2.5\) ks. We requested one more epoch with the UVW2 filter on 2017 April 1. We performed aperture photometry using a 5″ radius aperture and a 20″ background region using the uvotsource task in HEASoft. The measured magnitudes are reported in the AB system and have not been corrected for the host galaxy flux or Galactic extinction. We analyzed the simultaneous observations with Swift XRT (Burrows et al. 2005) in the 0.3–10 keV band with standard XRT analysis procedures (e.g., Evans et al. 2009) and convert from count rate to absorbed flux using a factor of 3.0 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ (cps)}^{-1} appropriate for a $kT_{bb} \sim 0.04$ keV blackbody (see Table 1).

In the optical Swift UVOT filters, the light curves plateau, indicating that the transient has likely faded below the host galaxy flux. We estimate the host galaxy flux from the plateau at $\Delta t > 300$ days after discovery to be $UVW1 = 21.50 \pm 0.1$, $U = 19.86 \pm 0.3$, $B = 18.42 \pm 0.2$, and $V = 17.74 \pm 0.1$ mag, respectively. The last $UVW$ detection at $t = 597$ days is $UVW2 = 22.37 \pm 0.18$ mag, which is below the archival GALEX upper limit of $NUV > 22.0$ mag, but almost 1 mag brighter than the synthetic UVOT host galaxy magnitude reported in Holoien et al. (2016a) of $UVW2 = 23.27 \pm 0.13$ mag. Thus, we assume that the UVW2 flux is still dominated by the transient. In Figure 1, we show the observed Swift UV/optical light curve, as well as the light curve with the host flux (estimated from the observed plateau flux level) subtracted off in the $UVW$, $U$, $B$, and $V$ filters. After this host flux subtraction, all six filters have a similar power-law decline with little evidence of color evolution.

2.2. XMM-Newton Observations

We triggered two epochs of TOO XMM-Newton 17 ks observations (PI: Gezari) on 2015 October 29 and 2016 April 4 with the EPIC-pn 0.2–12 keV detector in Full Frame mode with the thin filter. The data were reduced with the XMM-Newton Science Analysis System (XMM-SAS) software package version 15.0. After filtering for background flaring, we were left with 12.1 ks (MOS1), 12.5 ks (MOS2), and 10.3 ks (pn) of usable exposure time in 2015 and 15.5 ks (MOS1), 15.4 ks (MOS2), and 12.0 ks (pn) in 2016. We measured the X-ray flux in a 300 pixel aperture, with a background region measured in an annulus with a radius of 500 and 1500 pixels, respectively. We detect a total of 75 (MOS1), 69 (MOS2), and 453 (pn) counts in 2015 and 417 (MOS1), 386 (MOS2), and 2882 (pn) counts in 2016. Finally, we bin in energy to yield a minimum of 3 counts per bin. Given the much larger number of counts in the pn channel, we present our spectral analysis using the pn spectra.

3. Analysis

3.1. X-Ray Brightening

The 2015 Swift data reported in Holoien et al. (2016a) from 2015 August 29 to November 17 was fitted with two components, a soft blackbody with $kT = 49 \pm 9$ eV and a $\Gamma = 1.76 \pm 1.0$ power law, and with Galactic absorption fixed to $N_H = 5.59 \times 10^{20} \text{ cm}^{-2}$, and a total flux in the 0.3–10 keV band not corrected for Galactic absorption of $f_{abs} \sim (8.0 \pm 0.2) \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$. The X-ray flux was constant within the errors during this monitoring period, and the ROSAT archival upper limit ($f(0.3–10) \text{ keV} < 1.2 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$) was not constraining enough for Holoien et al. (2016a) to determine if this X-ray emission was indeed associated with the UV/optical transient.

Our first XMM-Newton epoch on 2015 October 29 was obtained during the Swift monitoring observations reported in Holoien et al. (2016a). Using the X-ray spectral fitting package XSPEC version 12.9.0, the spectrum is very well fitted with a blackbody plus power law ($\chi^2_{\text{red}} = 1.02$), with $kT_{bb} = 47.4 \pm 2.5$ eV and $\Gamma = 2.5 \pm 0.8$ with $f_{abs}(0.3–10 \text{ keV}) = 6.5 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$. The blackbody temperature and power-law index are both consistent within the errors of the model fit measured from stacking the Swift XRT observations in 2015. The second XMM-Newton epoch was taken on 2016 April 4, 234 days after the optical transient was discovered by the ASAS-SN survey. The spectrum is again well described with the blackbody
plus power-law model ($\chi^2_{\text{def}} = 1.21$), with $kT_{\text{bb}} = 42.3 \pm 0.7$ eV and $\Gamma = 3.3 \pm 1.3$ and with a total absorbed flux of $f_{\text{abs}}(0.3-10 \text{ keV}) = 3.7 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$. Note that while the power-law component normalization remains constant within the errors between the two epochs, the blackbody component normalization increases by a factor of $12 \pm 1$ (see Figure 2).

In the last Swift XRT observation on 2017 April 4, we detect a source with a count rate consistent with the Swift count rate measured in 2015. The brightening of the X-ray emission in 2016 thus places a lower limit on the X-ray flux associated with ASASSN-15oi of $f_{\text{abs}}(0.3-10 \text{ keV}) > 3 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$. The constant power-law ($\Gamma \sim 2.5$) component of the X-ray emission may be associated with an underlying low-luminosity active galactic nucleus (AGN) with $L(0.3-10 \text{ keV}) = 6.4 \times 10^{40}$ erg s$^{-1}$, for $d_L = 215$ Mpc and correcting for Galactic absorption. However, the extremely variable and soft blackbody component is most likely originating from the TDE, with a luminosity for the blackbody component corrected for Galactic absorption of $L(0.3-10 \text{ keV}) = 1 \times 10^{43}$ erg s$^{-1}$ at $\Delta t = 234$ days since discovery. The corresponding bolometric luminosity for the soft blackbody component is $\approx 3.8 \times 10^{41}$ cm$^{-1}$ and $2.1 \times 10^{42}$ cm, respectively, a factor of 5.5 increase in radius. The late-time decline in X-rays is consistent with what is expected for emission on the Wien tail of the thermal TDE emission, $L_X \propto \exp(A \tau^{-5/2})$, where $A$ is a constant that depends on the parameters of the event (Lodato &
Rossi 2011), suggesting that after 1 year, the X-rays are now more closely following the fallback rate.

The Swift XRT and XMM-Newton observations follow the brightening of the absorbed X-ray flux by a factor of 10 from \(~5 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \) to \(~5 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2} \) over a time period of 1 year (see Figure 3). This is in stark contrast to the fading of the UV flux by a factor of 100 over this same time period. This difference in temporal behavior, combined with the much larger inferred radius of the UV/optical emission from blackbody fits of \(10^{14} - 10^{15}\) cm (Holoien et al. 2016a), suggests that these components are physically distinct.

### 3.2. UV Fading

In Figure 3, we plot the total UV/optical flux by scaling the U/V2 flux density to match the bolometric flux measured from a blackbody fit to the UV/optical blackbody component 50–100 days after discovery reported by Holoien et al. (2016a). The UV/optical light curve decline at late times is shallower than the exponential decline with \(\tau = 46.5 \) day fitted by Holoien et al. (2016a) from the first 100 days of Swift monitoring and is steeper than the \(r^{-5/3}\) power-law decay expected for the bolometric luminosity evolution in a TDE (Phinney 1989; Lodato et al. 2009; Guillochon & Ramirez-Ruiz 2013). When we fit the light curve with a \(r^{-\alpha}\) power law, we find \(\alpha = 3 \pm 1\), but any single power-law model is unable to fit the plateau in UV/optical flux at late times.

### 3.3. Evolution of the Optical to X-Ray Ratio

In Figure 4, we plot \(L_{\text{opt}}/L_{\text{X}}\) in days since discovery for ASASSN-14li and ASASSN-15oi (Holoien et al. 2016a, 2016b), as well as for two GALEX TDEs that had X-ray detections in their late-time follow-up Chandra observations: D3-13 and D1-19 (Gezari et al. 2006, 2008). We do not plot TDEs with X-ray upper limits, such as PS1-10jh (Gezari et al. 2012), ASASSN-14ae (Holoien et al. 2014), iPTF16axa (Hung et al. 2017), and iPTF16fnl (Blagorodnova et al. 2017; Brown et al. 2018), since the X-ray band is on the Wien’s tail of the thermal emission expected from TDEs, and it is not clear if a non-detection in the 0.3–10 keV band of the X-ray detectors is due to a low flux or a very soft spectrum. For example, if the temperature of ASASSN-15oi had been just a little cooler, \(kT_{\text{bb}} \sim 30\) eV, the flux density at 0.3 keV would have been a factor of 50 fainter.

In the first year of monitoring ASASSN-15oi, there was a dramatic decrease in the UV/optical to X-ray \((0.3–10\) keV) luminosity ratio \((L_{\text{opt}}/L_{\text{X}})\) from \(~1000\) to \(~1\). This is in stark contrast to the relatively constant \(L_{\text{opt}}/L_{\text{X}} \sim 1\) observed in ASASSN-14li, the only other non-jetted TDE with a well-sampled X-ray light curve. And yet, the blackbody temperature and inferred radius for ASASSN-14li are very similar to that measured for the soft X-ray component of ASASSN-15oi, with \(kT_{\text{bb}} = 51\) eV and \(n_{\text{BB}} = 1.7 \times 10^{12} \text{ cm} = 11M_{\odot}^{-1}r_{E}\) (Miller et al. 2015).

### 4. Discussion

In order to compare the evolution of ASASSN-15oi to the relevant timescales for a TDE, we must first constrain its central black hole mass. Holoien et al. (2016a) estimate \(M_{\text{BH}} \sim 10^{7.1} M_{\odot}\) from its host galaxy mass of \(10^{10.0 \pm 0.1}\) (consistent with the errors from the estimate of van Velzen 2017 of \(10^{9.9} M_{\odot}\)) and assume a bulge-to-total mass ratio of \(0.575\) and the \(M_{\text{BH}}/M_{\text{bulge}}\) relation from McConnell & Ma (2013).

However, we note that in the study of the velocity dispersion \((\sigma)\) of TDE host galaxies by Wevers et al. (2017), they find that the inferred \(M_{\text{BH}}\) in TDEs are systematically higher when using the \(M_{\text{BH}}/M_{\text{bulge}}\) relation than when using the \(M_{\text{BH}}/\sigma\) relation. Similarly, AGNs are found to have black hole masses that lie an order of magnitude below the \(M_{\text{BH}}/M_{\text{bol}}\) relation established from dynamical studies of local galaxies with larger black hole masses than the AGN samples (Reines & Volonteri 2015). Reines & Volonteri (2015) do find a scaling relation between total stellar mass and black hole mass for AGNs with \(10^{8} M_{\odot} < M_{\text{BH}} < 10^{8}\) that would imply a black hole mass for the host galaxy of ASASSN-15oi of only \(10^{4.4 \pm 0.55}\) (Miller et al. 2015). Given the downward trend in the inferred black hole mass for ASASSN-15oi, we scale our equations to a \(10^{6}\) black hole.
The characteristic timescale for a TDE is set by the orbital period of the most tightly bound debris, known as the fallback time \( t_{fb} \), which for a solar-type star is

\[
 t_{fb} = 41 \text{ day} M_6^{1/2}.
\]

The circularization timescale \( t_{\text{circ}} \) driven by relativistic apsidal precession of the debris streams depends on the black hole mass as

\[
 t_{\text{circ}} = 8.3 t_{fb} M_6^{-5/3} \beta^{-3},
\]

where \( \beta = R_t / R_p \) (Bonnerot et al. 2016). Meanwhile, the viscous inflow timescale for a standard \( \alpha \)-disk model (Shakura & Sunyaev 1973) is

\[
 t_{\text{visc}} = \alpha^{-1} (h/r)^{-2} P_{\text{out}} \sim 0.1 t_{fb} (\alpha/0.1)^{-1} (h/r)^{-2},
\]

where \( \alpha \) is the standard viscous parameter, \( h \) is the scale-height of the disk, and \( P_{\text{out}} \) is the orbital period of the outer edge of the disk.

In the case of inefficient circularization, there will be a “viscous delay” between the fallback time and the onset accretion of the debris though a disk (Shiokawa et al. 2015). In Guillochon & Ramirez-Ruiz (2015), they predict a population of “viscously delayed” TDEs from lower-mass back holes \((M_{\text{BH}} \lesssim 10^6 M_\odot)\) with weaker stream–stream collisions as a consequence of weaker relativistic precession that result in longer timescales and lower accretion rates. The circularization timescale \( t_{\text{circ}} \) for a 10\(^6\) \( M_\odot \) black hole is tantalizingly close to the \( \sim 1 \) year rise-time to peak observed in the soft X-rays for ASASSN-15oi and may indicate that we are indeed seeing delayed accretion due to inefficient circularization of the debris disk. The blackbody radii inferred from the XMM-Newton observations are indeed consistent with the inner parts of an accretion disk, with \( r_{bb} = 3 M_6^{1/2} r_g \) on 2015 October 29 and \( r_{bb} = 15 M_6^{-1} r_g \) on 2016 April 4, where \( r_g = GM/c^2 = 1.5 \times 10^{11} M_6 \text{ cm} \) and the slow expansion rate \((\sim 1 \text{ km s}^{-1})\) may be tracing the viscous spreading of the newly formed accretion disk. (Note that if the black hole mass in ASASSN-15oi is in fact closer to \( 10^7 M_\odot \), then the inferred circularization timescale is a factor of 15 times shorter and its blackbody radius a factor of 10 smaller in units of \( r_g \).)

Another scenario is that the accretion disk is enthroned in material that is optically thick to soft X-rays. In this case, the soft X-ray radiation can eventually “break out” once the obscuring material expands enough to become fully ionized (Metzger & Stone 2016). The nature of this expansion could be attributed to a radiatively driven outflow, or from the evolution of the circularizing debris streams themselves, which are expected to form a plume of debris that expands due to energy dissipated from the shocked streams (Jiang et al. 2016). Auchettl et al. (2017) suggested that the ratio of X-ray to optical power observed in TDEs is related to the Eddington ratio, where TDEs with higher accretion rates have more material available to obscure the X-ray emission. In the case of ASASSN-15oi, since the soft blackbody component of the X-ray emission is detected at early times, it can only have been partially veiled. Furthermore, the lack of evidence for a decrease in absorbing column density in ASASSN-15oi with the increasing X-ray luminosity argues against the “veiled” TDE scenario.

Finally, we can rule out that the X-ray properties of ASASSN-15oi are due to a viewing angle effect since the orientation of the black hole and debris stream are not expected to change on the timescales observed for the X-ray to optical flux evolution in ASASSN-15oi.

### 5. Conclusions

We present the brightening by a factor of \( \sim 10 \) of the soft X-ray luminosity in TDE ASASSN-15oi measured by Swift and XMM-Newton on a timescale of 1 year after discovery. The decoupled behavior of the brightening soft X-ray emission relative to the fading UV/optical emission suggests that they arise from physically distinct components. The timescale and spectrum of the delayed soft X-ray peak is consistent with the circularization timescale and inner radius of a TDE debris disk around a \( \sim 10^6 M_\odot \) black hole. The prompt onset of the UV/optical emission is then naturally explained if it originates in shocks in the debris streams in the process of circularization (Lodato et al. 2012; Piran et al. 2015) and may apply to the nature of optical emission in TDEs in general.

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Gezari, Cenko, & Arcavi
The Astrophysical Journal Letters, 851:L47 (6pp), 2017 December 20

Gezari, Cenko, & Arcavi

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6