Chandra, HST/STIS, NICER, Swift, and TESS Detail the Flare Evolution of the Repeating Nuclear Transient ASASSN -14ko

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Received 2022 June 22; revised 2023 May 1; accepted 2023 May 1; published 2023 July 10

Abstract

ASASSN-14ko is a nuclear transient at the center of the AGN ESO 253−G003 that undergoes periodic flares. Optical flares were first observed in 2014 by the All-Sky Automated Survey for Supernovae (ASAS-SN) and their peak times are well-modeled with a period of 115.2±1.2 days and period derivative of −0.0026±0.0006. Here we present ASAS-SN, Chandra, HST/STIS, NICER, Swift, and TESS data for the flares that occurred on 2020 December, 2021 April, 2021 July, and 2021 November. These four flares represent flares 18–21 of the total number of flares observed by ASAS-SN so far since 2014. The HST/STIS UV spectra evolve from blueshifted broad absorption features to redshifted broad emission features over ~10 days. The Swift UV/optical light curves peaked as predicted by the timing model, but the peak UV luminosities that varied between flares and the UV flux in Flare 20 were roughly half the brightness of the other peaks. The X-ray luminosities consistently decreased and the spectra became harder during the UV/optical rise, but apparently without changes in absorption. Finally, two high-cadence TESS light curves from Flare 18 and Flare 12 showed that the slopes during the rising and declining phases changed over time, which indicates some stochasticity in the flare’s driving mechanism. Although ASASSN-14ko remains observationally consistent with a repeating partial tidal disruption event, these rich multi-wavelength data are in need of a detailed theoretical model.

Unified Astronomy Thesaurus concepts: Black holes (162); Active galactic nuclei (16); High energy astrophysics (739)

Supporting material: machine-readable table

1. Introduction

A tidal disruption event (TDE) occurs when a star crosses the tidal radius of a central supermassive black hole (SMBH) and is torn apart by the SMBH’s tidal forces (Hills 1975; Rees 1988; Phinney 1989; Evans & Kochanek 1989). This results in roughly half of the stellar mass becoming unbound and the remainder forming an accretion disk that feeds the SMBH, producing a luminous multi-wavelength flare. TDEs exhibit diverse behaviors across the electromagnetic spectrum. This includes a wide range of X-ray brightening timescales and luminosities (e.g., Auchettl et al. 2017; Holoien et al. 2018; Wevers et al. 2019; Kajava et al. 2020; Hinkle et al. 2021b); optical spectral properties, such as the presence or absence of Hydrogen, Helium, and Bowen fluorescence lines (e.g., Gezari et al. 2012; Arcavi et al. 2014; Holoien et al. 2014a, 2016a, 2016b, 2018, 2020; Brown et al. 2016, 2017; Leloudas et al. 2019; Nicholl et al. 2019; van Velzen et al. 2021; Hinkle et al. 2023); and differences in their blackbody luminosity, radius, and temperature evolution (Hinkle et al. 2020, 2021a).

The ultraviolet (UV) spectral properties of TDEs are less well explored. The small sample of TDEs with UV spectra includes ASASSN-14li (Cenko et al. 2016), iPTF-16fnl (Brown et al. 2018), iPTF-15af (Blagorodnova et al. 2019), PS18kh (AT 2018qrz: Hung et al. 2019), and ZTF19abzhrbg (AT 2019qiz: Hung et al. 2021), in addition to the ambiguous nuclear transient (ANT) ASASSN-18jd that showed properties indicative of both TDEs and active galactic nuclei (AGNs; AT 2018bcb; Neustadt et al. 2020). The UV spectra of TDEs are generally characterized by a hot continuum and broad lines, including Lyα, N V λ1240, Si IV λ1390, and C IV λ1550 in emission and absorption. Somewhat surprisingly, they show little temporal evolution when multiple epochs are available. To date, UV spectra have only been obtained after maximum light and during the decline, weeks to months after maximum light. The UV spectra of AGN are characterized by broad and narrow emission lines on top of a roughly power-law.
continuum spectrum (e.g., Krolik 1999). Typical spectral features include $\lambda\alpha$ 1215, CIV $\lambda$1549, SiIV $\lambda$1400, N V $\lambda$1240, O V $\lambda$1035, CIII] $\lambda$1908, and Mg II $\lambda$2800, as well as broad absorption lines, which are generally on the blue wing of the lines. Both the lines and the continuum are time variable. The vast majority show modest levels of continuum variability that are reasonably, but not perfectly, modeled by a damped random walk stochastic process (e.g., Kelly et al. 2008; Kozlowski et al. 2010; MacLeod et al. 2010; Zu et al. 2013). Meanwhile, the UV continuum variability drives changes in the broad emission lines, which are frequently studied using reverberation mapping (Blandford & McKee 1982; Peterson 1993; Peterson et al. 2004). In particular, the emission lines are observed to narrow as the AGN becomes brighter, as expected from photoionization models.

A small fraction of AGNs are “changing-look quasars” where the structure of the emission lines completely changes between narrow and broad line dominated spectra, usually with a significant change in the continuum brightness (e.g., Bianchi et al. 2005; Denney et al. 2014; Shappee et al. 2014; MacLeod et al. 2016; Hon et al. 2022). In the case of “rapid turn-on” events, the blue continuum and broad lines appear on timescales of a few months (e.g., Gezari et al. 2017; Frederick et al. 2019; Gromadzki et al. 2019; Trakhtenbrot et al. 2019a; Ricci et al. 2020). There are also ANTIs that share the characteristics of both TDEs and more normal AGN variability (Neustadt et al. 2020; Hinkle et al. 2022; Holoien et al. 2022; Yu et al. 2022).

Here, we present observations of the latest four flares of ASASSN-14ko, which is a nuclear transient at the center of the AGN ESO 253−G003 that undergoes periodic flares (Payne et al. 2021, 2022). This transient was initially discovered by the All-Sky Automated Survey for Supernovae (ASAS-SN, Shappee et al. 2014; Kochanek et al. 2017) in 2014 but was classified as a Type IIn supernova with a blue continuum projected very close to the nucleus of a Type 2 Seyfert, although AGN activity was not ruled out as a possibility (Holoien et al. 2014b). However, the subsequent seven years of ASAS-SN data revealed that the flare was not a one-time event—the flares recur at regular intervals that are well-fitted by a timing model with a mean period of roughly 115 days and a negative period derivative. Each flare is consistently characterized by a single UV/optical brightening event that rapidly rises and smoothly declines over ~40 days. The X-ray flux dims rapidly (days) during the UV rise and then recovers. The host galaxy ESO 253−G003 is a complex merger remnant with two AGNs and a large tidal arm (Tucker et al. 2021). The brighter northeastern nucleus is the source of the periodic flares (Payne et al. 2022).

In this paper, we present the data and analysis of the four flares that peaked in 2020 December, 2021 April, 2021 July, and 2021 November which are flares 18–21 of the total number of flares observed by ASAS-SN since 2014. We will refer to these events by their respective number throughout the text. In Section 2, we discuss the data that we used in this paper. In Section 3, we show the photometric light curves, the updated timing model, and we describe how the latest flares compare to the previous flares. In Section 4, we analyze the UV spectra, and in Section 5 we investigate the X-ray emission. In Section 6, we discuss how the latest flares fit into interpretations of ASASSN-14ko’s origins and we give our conclusions in Section 7. For a flat $\Omega_m = 0.3$ universe, the luminosity distance is $\approx 188$ Mpc and the projected scale is $\approx 0.85$ kpc/arcsec. The Galactic extinction is $A_V = 0.116$ mag (Schlafly & Finkbeiner 2011).

### Table 1

| MJD     | Band | $L_\lambda$ (erg s$^{-1}$) | $L_\lambda$ Error (erg s$^{-1}$) |
|---------|------|-----------------------------|-----------------------------------|
| 58983.65 | X-ray | 186                         | 50.3                              |
| 58983.65 | W2    | 4.89                        | 0.29                              |
| 58983.68 | M2    | 3.99                        | 0.43                              |
| 58983.65 | W1    | 2.29                        | 0.16                              |
| 58983.65 | U     | 1.15                        | 0.09                              |
| 58983.65 | B     | 0.82                        | 0.08                              |
| 58983.66 | V     | 0.62                        | 0.08                              |
| 58849.34 | $g$   | 0.63                        | 0.08                              |
| 58425.46 | $I_{\text{TESS}}$ | 0.019                      | 0.005                             |

**Note.** The luminosities are in units of $10^{43}$ ergs s$^{-1}$ and the X-ray luminosities are between 0.3–10.0 keV. Only the first observation in each band is shown here to demonstrate its form and content. The table is published in its entirety in machine-readable form in the online journal.

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ASAS-SN is an ongoing all-sky survey that uses four 14 cm telescopes on a common mount to monitor the sky to find bright and nearby transients (Shappee et al. 2014; Kochanek et al. 2017). There are currently five units, which are located in Hawai`i, Chile, Texas, and South Africa, and are hosted by the Las Cumbres Observatory global telescope network (Brown et al. 2013). ASAS-SN images are processed with a fully automatic pipeline that utilizes the ISIS image subtraction package (Alard & Lupton 1998; Alard 2000). Reference images are used to subtract the background and host emission from all science images, and aperture photometry is then performed using the IRAF $apphot$ package (Tody 1986, 1993). The data were calibrated using stars from the AAVSO Photometric All-Sky Survey (APASS; Henden et al. 2015). All of the low-quality images were inspected by eye and images that were affected by clouds or other systematic problems were removed.

### 2. Observations

The following sections describe the data that we used in this analysis. All of the photometric data discussed here are presented in Table 1.

#### 2.1. ASAS-SN

ASAS-SN is an ongoing all-sky survey that uses four 14 cm telescopes on a common mount to monitor the sky to find bright and nearby transients (Shappee et al. 2014; Kochanek et al. 2017). There are currently five units, which are located in Hawai`i, Chile, Texas, and South Africa, and are hosted by the Las Cumbres Observatory global telescope network (Brown et al. 2013). ASAS-SN images are processed with a fully automatic pipeline that utilizes the ISIS image subtraction package (Alard & Lupton 1998; Alard 2000). Reference images are used to subtract the background and host emission from all science images, and aperture photometry is then performed using the IRAF $apphot$ package (Tody 1986, 1993). The data were calibrated using stars from the AAVSO Photometric All-Sky Survey (APASS; Henden et al. 2015). All of the low-quality images were inspected by eye and images that were affected by clouds or other systematic problems were removed.

#### 2.2. HST/STIS

We observed ASASSN-14ko using STIS and the FUV/NUV MAMA detectors (HST IDs: 16451, 16498; PI: Shappee). We used the $52^\circ 0 \times 0^\prime 2$ slit and the G140L (1425 Å, FUV-MAMA) and G230L (2376 Å, NUV-MAMA) gratings. FUV and NUV spectra were obtained on 2020 December 18 (MJD 159201.6), 2020 December 22 (MJD 159205.6), 2020 December 29 (MJD 159212.3), 2021 March 6 (MJD 159279.1), and FUV-only spectra were obtained on 2021 March 29 (MJD 159302.6) and 2021 April 1 (MJD 159305.3). Each visit consisted of two or three exposures per grating, with exposure times ranging from 336 to 482 s for the G230L grating and 200–1732 s for the G140L grating. We used the one-dimensional spectra produced by the HST pipeline because the trace of ASASSN-14ko was clearly present in the two-dimensional spectra.
dimensional frames. For each epoch, we combined the individual exposures with an inverse-variance-weighted average of the one-dimensional spectra, and we then merged the FUV and NUV channels. All of the HST/STIS data that are used in this paper can be found in MAST: DOI: 10.17909/hk87-6g84.

2.3. Swift XRT and UVOT

We requested Swift ToO observations (ToO ID: 14775, 14971, 15393, 15636, 16037, 16546; PI: Payne) using the UltraViolet/Optical Telescope (UVOT) and the X-Ray Telescope (XRT) to coincide with the predicted Flares 18–21. The UVOT data were obtained in six filters (Poole et al. 2008); $V$ (5425.3 Å), $B$ (4349.6 Å), $U$ (3467.1 Å), $UVW1$ (2580.8 Å), $UVM2$ (2246.4 Å), and $UVW2$ (2054.6 Å). The wavelengths used here are the pivot wavelengths calculated by the SVO Filter Profile Service (Rodrigo et al. 2012). The Swift team announced in 2020 November that a loss of sensitivity over time requires an updated photometric correction for the three UVOT UV filters, and we used the updated correction for this analysis (see Hinkel et al. 2021a). We used the HEASoft (HEASARC 2014) software tool uvotsource to extract the source counts using a 16″ radius aperture and used a sky region of ∼40″ radius to estimate and subtract the sky background.

The XRT data were reduced using the HEASoft tool xrtpipeline. We obtained a background subtracted count rate from each observation using a source region with a radius of 50″ centered on the position of ASASSN-14ko and a 150″ radius source free background region centered at $(\alpha, \delta) = (05^h25^m09^s87, -45°56'47"94)$. All of the count rates were corrected for encircled energy fraction. To estimate the X-ray luminosity of ASASSN-14ko, we convert the derived count rate into an X-ray flux using the count rate simulator WebPimms. Here, we assume an absorbed power law with an average photon index derived from fitting our Swift ($\Gamma = 1.3$) and NICER ($\Gamma = 1.85$) spectra; therefore, a final photon index of $\Gamma = 1.57$ for the simulations and a column density of $3.49 \times 10^{20} \text{cm}^{-2}$ (HI4PI Collaboration et al. 2016).

2.4. TESS

The Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014) observed ASASSN-14ko during Sectors 31–33, which occurred between 2020 October 21 and 2021 January 13, with the flare occurring during Sectors 32–33. Following a similar procedure to that used for the ASAS-SN data, we used the ISIS package to perform image subtraction on the 10 minutes cadence full frame images (FFIs) to obtain high fidelity light curves, as described in Vallety et al. (2019, 2021). This is the second flare that has been captured by TESS, following an earlier observation during Sectors 3–5 of the flare that peaked in Flare 12 (Payne et al. 2022).

2.5. NICER

ASASSN-14ko was also observed using the Neutron star Interior Composition ExploreR (NICER; Gendreau et al. 2012) and its X-ray timing instrument (XTI). ASASSN-14ko was observed for a total of 115 times between 2020 December 10 and 2021 December 1 (ObsIDs: 3201740101–3201740118, 4662010101–4662022801, PI: Payne), for a total cumulative exposure of 277.7ks.

The data were reprocessed using the NICERDAS version 8 c and the task NICERL2. Here, standard filtering criteria were used, as well as the latest gain and calibrations files. Time averaged spectra and count rates were extracted using XSELECT. We used the ARF (nixtiaveonaxis20170601v005.arf) and RMF (nixtiref20170601v003.rmf) files that are available with the NICER CALDB. All of the spectra were grouped using a minimum of 20 counts per energy bin. Since NICER is a non-imaging instrument, background spectra were generated using the background modeling tool NIBACKGEN3C50. We converted from observed count rate to luminosity using the method that was described in Section 2.3.

2.6. Chandra

Finally, we acquired two Chandra ACIS-S DDT observations (observation IDs: 24875, 24876; PI: Payne). The first observation occurred on 2020 December 26 with an exposure time of 27.69 ks, and the second observation occurred on 2021 January 21 with an exposure time of 28.68 ks. The data were analyzed using CIAO 4.13 and CALDB 4.9.4. The data were reduced using the CIAO command CHANDRA_REPRO, while spectra were extracted from each reprocessed observation using the CIAO command SPECEXTRACT. All of the spectra were grouped using a minimum of 20 counts per bin. To analyze the spectral data from Swift, NICER, and Chandra data, we used the X-ray spectral fitting package (XSPEC) version 12.12.0 (Arnaud 1996) and $\chi^2$ statistics.

3. UV/Optical Light Curve Analysis

Flares 18–21 are the third through sixth events, respectively, in which the UV properties were observed in conjunction with the optical evolution. These data enable us to search for similarities and differences in the UV properties of six flares.

3.1. UV/Optical Evolution

We showed previously in Payne et al. (2021) and Payne et al. (2022) that ASASSN-14ko’s flares are essentially periodic, so each new flare is another opportunity to update the timing model of the optical peaks. In Payne et al. (2021), we found significant residuals between the observed and calculated peak times (Observed − Calculated, $\theta − \bar{C}$), which is indicative of a period derivative. To analyze how this trend continued, we measured the optical peaks of Flares 18–21 by fitting the ASAS-SN $g$-band light curves with a fifth-order polynomial and measured the errors on the peak times by bootstrap resampling the data. These peaks occurred on $59205.7 \pm 0.19$, $59315.2_{-0.3}^{+0.5}$, $59433.3_{-0.2}^{+0.7}$, and $59532.2 \pm 0.9$, respectively. The comparatively larger error in Flare 20’s peak timing is caused by a gap in the ASAS-SN light curve due to bad weather, so we also measured this event’s peak timing using the Swift $B$-band light curve whose peak time was $59423.9_{-1.2}^{+0.7}$. After combining the new flares reported here with those in Payne et al. (2021) and Payne et al. (2022), 21 flares that have now been observed by ASAS-SN since 2014.

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12 https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl
13 See Bogdanov et al. (2019) or Section 2.7 of Hinkel et al. (2021b).
14 https://heasarc.gsfc.nasa.gov/docs/nicer/tools/nicer_bkg_est_tools.html
For Flare 12 and Flare 18, TESS also observed these flares. Therefore, the peak times measured from the TESS light curves were also included alongside the peak times measured from ASAS-SN. We fit the model

\[ t = t_0 + nP_0 + \frac{1}{2}n^2P_0\dot{P} + \frac{1}{6}n^3P_0\dot{P}^2, \]

and obtain starting time \( t_0 = 2456852^{+10}_{-11} \) JD, mean period \( P_0 = 115.2^{+1.3}_{-1.2} \) days, and a period derivative \( \dot{P} = -0.0026 \pm 0.0006 \). The errors on the peak times were expanded in quadrature by 0.8 day to obtain a reduced \( \chi^2 \) of unity for 10 degrees of freedom. The \( O - C \) diagram for all observed peaks with the updated timing model is shown in Figure 1. The parabolic trend in the \( O - C \) timings continues. This timing model predicts that the next flares will peak in the optical on MJD 59639.7 (UT 2022-03-01.2), 59747.5 (UT 2022-06-17.0), 59855.9 (UT 2022-10-03.4), 59962.1 (UT 2023-01-17.6), and 60069.0 (UT 2023-05-04.5).

In Payne et al. (2022), we concluded that \( \dot{P} \) had changed and used only the flare timings obtained after flare 9 for the timing model to predict when subsequent flares would occur. With these four new flares it now seems that the timing of Flare 10 and Flare 11 were anomalous and the older (Flares 1–9) and recent flares (Flares 12–21) are consistent with a single \( \dot{P} \). Certainly, for a repeating TDE we should expect some stochasticity in \( \dot{P} \)—it would be problematic for this interpretation if \( \dot{P} \) did not vary.

After updating the timing model following each new flare, we used the latest predictions to schedule the observations of the next flare. Figure 2 shows the UV/optical host-subtracted light curves for the six most recent flares, Flares 16–21. To directly compare the flare evolution across all of the flares, we stacked the host-subtracted light curves using the optical peak times predicted by the timing model, as shown in Figure 3. The flares are consistently characterized by a single, asymmetric UV and optical rise and fall without obvious substructure. The six flares are not identical. The peak UV luminosity changes and the differences are largest in the shortest wavelength W2 and M2 UV bands. This contrasts with the optical bands, which have not shown discernible changes in peak luminosity between flares. Flare 20 was significantly less luminous than all of the others across all bands except for the V-band, which was noisier. So, Flare 20 was the first indication that the flares can have significantly different peak luminosities.

We fit a blackbody model to the UV+U SED as we have done with previous nuclear transients (e.g., Hinkle et al. 2020). We used Markov Chain Monte Carlo methods to find the best-fit blackbody parameters for the SED, using flat priors of 1000 K \( \leq T \leq 55,000 \) K and \( 10^{11} \) cm \( \leq R \leq 10^{17} \) cm in order to not overly influence the fits. The evolution in luminosity, effective radius, and temperature from these blackbody fits are shown in Figure 4. The blackbody models were poor fits if we included the \( B \) and \( V \) data. This could be due to deviations from a blackbody SED as a consequence of assuming that the inter-flare flux is just the host galaxy. Since the UV dominates the energetics, using UV+U only should still give a reasonable characterization of the flares. For all of the flares observed in the UV, the peak blackbody luminosity and temperature occurred several days before the corresponding ASAS-SN g-band peaks. The blackbody radius begins to decline around the times of the g-band peaks. The peak blackbody luminosities of the flares were all consistent except for Flare 20, which was fainter but had a similar peak blackbody radius to the others. This is consistent with the luminosity evolution shown in Figure 3.

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**Figure 1.** \( O - C \) plot for all of ASASSN-14ko’s observed outbursts comparing the time of the observed peak with the estimated peak if we assume a constant period. The black circles correspond to the the flares reported in Payne et al. (2021, 2022) and the blue squares represent the flares reported here. The solid line is the model described in Section 3.1.
Figure 2. The Swift and NICER X-ray and UV luminosities and hardness ratios for the six flares in 2020–2021. The vertical-dashed lines indicate the g-band peaks predicted from the updated timing model described in Section 3. The vertical-solid bars are color-coded to the HST/STIS spectra epochs shown in Figure 6 and the Chandra spectra epochs shown in Figure 11. Upper limits are indicated by downward facing triangles. The X-ray luminosities cover 0.3–10.0 keV, and the hard and soft X-rays are defined between 0.3–2.0 keV and 2.0–10.0 keV, respectively.
Figure 3. Swift XRT and NICER X-ray and host-subtracted Swift UVOT, and ASAS-SN g-band light curves aligned using the updated timing model described in Section 3, including Flare 16 (circles), Flare 17 (triangles), Flare 18 (squares), Flare 19 (pentagons), Flare 20 (stars), and Flare 21 (Xs) flares. The vertical bars are color-coded to the HST/STIS spectra epochs shown in Figure 6 and the Chandra spectra epochs shown in Figure 11.
3.2. TESS Light Curve Analysis

TESS observed ASASSN-14ko’s flares during Sectors 3–5, which captured Flare 12 (Payne et al. 2021), and again during Sectors 31–33 for Flare 18. TESS’s second view of ASASSN-14ko’s flaring behavior enables us to compare the properties of two individual flares using high-cadence data to investigate how they changed over that two year time frame. We aligned the data using the updated timing model and plot this in Figure 5. Due to the timing of the TESS sectors, the full decline was not captured for Flare 18 but the full rise to peak was observed.

Previous TDEs and some supernovae have been fitted by the model

\[ f(t) = f_0 + f_1(t - t_0)^\alpha \]  

finding \( \alpha \approx 1.9 - 2.8 \) (ASASSN-19bt with \( \alpha = 2.10 \pm 0.12 \), Holoien et al. 2019; ASASSN-19dj with \( \alpha = 1.9 \pm 0.4 \), Hinkle et al. 2021b; ZTF19abzrhg with \( \alpha = 1.99 \pm 0.01 \), Nicholl et al. 2020). In Payne et al. (2021), we fit the first 25% of Flare 12 rise with a single power-law to find \( \alpha = 1.01 \pm 0.07 \). There is a certain arbitrariness to these models in selecting the time period over which to do the fit because the actual light curve has to deviate from the power law as it approaches the peak. The sector shift during the rise in Flare 18 also makes it difficult to use this model.

Here, we instead use the model used by Vallely et al. (2021) to model the rise time of core-collapse supernovae with TESS data,

\[ f(t) = \frac{h}{(1 + z)^2} \left( \frac{t - t_1}{1 + z} \right)^{\alpha(1 + \alpha) / \alpha + \eta(1 + \eta)} + f_0 \]  

up to near the light curve peak for \( t > t_1 \) and as \( f(t) = f_0 \) for \( t < t_1 \). Here, \( f_0 \) is any residual background flux, \( t_1 \) is the beginning of the model rise, and the factors of \( 1 + z \) are introduced to account for

Figure 4. Evolution of ASASSN-14ko’s luminosity (top), effective radius (middle), and temperature (bottom) from blackbody fits to the host-subtracted UV/optical Swift data. The colors and symbols match those used in Figure 3 and the data are aligned using the timing model described in Section 3.
redshift time-dilation, although the low redshift of the host galaxy makes the correction small. Parameter $a_2$ is mathematically related to the rise time, $t_{\text{rise}} = t_{\text{peak}} - t_1$, between the start of the rise at time $t_1$ and the time of the peak $t_{\text{peak}}$. This model is able to adjust to the changing curvature as the transient approaches its peak, and can therefore be fitted over a broad enough time range for the slope of the initial rise to be unaffected by this choice (although the parameters for the curvature approaching the peak will be). Using this model, we find $a_1 = 1.10 \pm 0.04$ and $a_1 = 1.50 \pm 0.10$ for Flare 12 and Flare 18, respectively. The fits for both flare events using Equation (3) are shown in Figure 5. The fit parameters are summarized in Table 2. For our estimates of $t_{\text{rise}}$, we estimate $t_{\text{peak}}$ directly from the light curve using a polynomial fit to the data around peak. As shown by these model fits in Figure 5, Flare 18 started to rise earlier and took a day longer to rise to peak than Flare 12. In addition, Flare 18 took longer to rise to 50% of the peak flux. We refit the previously studied TDEs with publicly available photometric data with observed early-time rises.
with Equation (3) to compare to ASASSN-14ko and found $\alpha_1 = 5.12 \pm 0.12$ and $\alpha_2 = -0.02 \pm 0.001$ for ASASSN-19bt, and $\alpha_1 = 1.70 \pm 0.44$ and $\alpha_2 = -0.01 \pm 0.001$ for ASASSN-19dj. The early-time rise of ASASSN-14ko is similar to ASASSN-19dj but different than ASASSN-19bt.

Like Flare 12 (Payne et al. 2021), Flare 18 also smoothly declined in brightness, as shown in Figure 5. As in Payne et al. (2021), we fit the decline of both flares using a power-law and exponential model. Since only part of the decline was captured for Flare 18, we fit both flares over this restricted time range (3–21 days after peak). The power-law model is

$$f(t) = z - h \left( \frac{t - t_0}{\text{days}} \right) \alpha$$

with $t_0$ being the time of disruption, constrained to be before the start of the rise, $t_1$, as determined above. However, in Payne et al. (2021) we found that an exponential decline

$$f(t) = ae^{-\left(\frac{t-t_\text{peak}}{\tau}\right)} + c$$

was a better fit for Flare 12. We find that Flare 18 flare is also best fitted by the exponential model with a reduced $\chi^2$ of 0.80 with 2419 degrees of freedom versus a reduced $\chi^2$ of 1.02 with 5851 degrees of freedom for the power-law model fit after inflating the errors to give the power-law model a reduced $\chi^2 \simeq 1$. There is a difference in the degrees of freedom because the power-law model also includes the pre-rise quietness data as part of the fit, whereas the exponential model does not. The best-fit parameters for both models are also shown in Table 2.

Compared to Flare 12, Flare 18 began to rise earlier but took longer to rise to a fainter peak and then declined more slowly. Although the full decline was not observed by TESS, it is likely that Flare 18 also took longer to return to quiescence than Flare 12.

### 4. UV Spectroscopic Analysis

We present the six epochs of HST/STIS UV Galactic extinction corrected spectra in Figure 6. They were obtained during both the UV rise and decline for Flare 18, as denoted by the color-coded vertical bars in Figure 3. We also obtained two UV spectra a few days prior to the start of the UV rise of Flare 19 when the X-ray flux was anticipated to be in a low state based on the Swift XRT light curves of the prior flares (see Section 5).

There were dramatic changes in both the UV continuum and the spectral lines as Flare 18 evolved. The FUV continuum was at its bluest state in the first observation −4 days prior to the optical peak and when the UV flux was still increasing. Several days later at epochs of +0 and +7 days, when the UV flux was declining, the UV continuum flattened. The continuum was faintest at −36, −12, and −9 days.

The spectral lines during the flare are very different from the quiescent spectrum, as shown in Figure 6, where we also offset each epoch to show the change in spectral features over time. The prominent features are the standard UV lines of AGNs, including Ly\(\alpha\), N \(\lambda\)1240, Si IV \(\lambda\lambda\)1394, 1403, C IV \(\lambda\lambda\)1548, 1550, C III\(\lambda\)1909, and Mg II \(\lambda\lambda\)2796, 2800. In addition to these features, we detect narrow-, high-, and low-ionization absorption features at $z = 0$, which we interpret as originating from the Milky Way ISM (as discussed in the Appendix).

The evolution of the spectral lines over the duration of the flare is most dramatic for Ly\(\alpha\), N \(\lambda\)1240, Si IV \(\lambda\lambda\)1394, 1403, and C IV \(\lambda\lambda\)1548, 1550. We fit either single or multiple-component Gaussian models to Si IV, C IV, C III, and Mg II, as shown in Figure 7, with the resulting fit parameters summarized in Table 3. We estimated the local continuum by fitting a polynomial to the adjacent featureless regions surrounding the lines. Although it appears that Ly\(\alpha\)+N \(\lambda\) shows a similar trend in its profile evolution, we do not fit these profiles due to the complexity created by the blended lines and the telluric features. The velocities of each component were then obtained using these fits. Most components have velocities on the order of several thousand km s\(^{-1}\). During the UV rise at −4 days, a strong blue absorption feature is seen for the Si IV and C IV lines, which weakens and then vanishes during the declining phase of the UV light curve. The absorption feature is also absent in the quiescent spectrum. The presence of the absorption feature is clearest for the C IV \(\lambda\lambda\)1548 and Si IV \(\lambda\lambda\)1394, 1403 lines because there are no other nearby lines. The velocity of this feature is $\sim$4000–5000 km s\(^{-1}\). Based on the evolution of the C IV \(\lambda\lambda\)1548 and Si IV \(\lambda\lambda\)1394, 1403 lines, the strong absorption feature centered at 1235 Å is possibly associated with the blue wing of N \(\lambda\)1240. As the absorption features vanish, broad emission lines of C IV and Si IV appear with similar velocity widths but $\sim$4000 km s\(^{-1}\) redwards of the absorption features. C III\(\lambda\)1909 and Mg II are only seen in emission and show only modest changes. The presence of Mg II is a significant difference from all of the previous UV spectra of TDEs.

We obtained two UV spectra on 2021 March 29 and 2021 April 1, −12 and −9 days prior to the optical peak to determine the spectral properties at the time of the minimum X-ray emission. There were no large differences between these two spectra and the quiescent spectrum from 2021 March 6, aside from the appearance of a weak absorption feature on the blue side of C IV in the −9 days spectrum and at the X-ray minimum. This feature may be the beginning of the prominent blue absorption feature that was present at −4 days relative to peak. There was a significant difference in the minimum X-ray luminosity between the two flares, with Flare 18’s minimum
being significantly fainter than Flare 19’s minimum for both the total and soft X-ray luminosity (as discussed below).

5. Analysis of the X-Ray Emission

As previously shown in Payne et al. (2021, 2022), ASASSN-14ko’s X-ray evolution during the flares differs from its UV/optical evolution. The X-ray luminosity rapidly drops during the UV/optical rise, recovers near the peak, and then declines again before recovering. Here, we discuss the new X-ray data from Swift and NICER during Flares 18–21.

Figure 6. HST/STIS UV spectra of ASASSN-14ko during Flare 18 and Flare 19. The −4 (blue), +0 (orange), and +7 (red) days spectra are relative to Flare 18’s optical peak timing of MJD 59205.65, and the −36 (black), −12 (pink), and −9 days (purple) spectra are relative to Flare 19’s optical peak timing of MJD 59315.22. The spectra have been corrected for Galactic extinction and the major geocoronal airglow lines are marked with the green ⊕ symbol. The middle panel shows the full spectra offset to better illustrate the change in line profiles over time. The bottom panels are zoomed-in to the labeled lines and not offset, showing the change in flux at different epochs of the flares. The major BALs are shaded in purple, blue, and green regions.

5.1. X-Ray Light Curve from Swift XRT and NICER

Similar to what was presented in Payne et al. (2021, 2022), and what we used for our Chandra spectra (Section 5.2), we modeled both the merged Swift data and the extracted NICER spectra using an absorbed power law that was redshifted to the distance of the host (TBABS*ZSHIFT*POWERLAW). To fit the data, we let the column density, power-law index, and normalization be free. For the merged Swift data, spectral fitting was performed over an energy range of 0.5–5.0 keV, while for the NICER data the spectral fitting was performed over an energy range of 0.5–2.0 keV.
to avoid energy ranges where the background begins to dominate the spectrum. In Figure 8, we plot representative NICER and merged Swift X-ray spectra with the best-fit models and the corresponding background spectra, while in Figure 3 we plot our best-fit column densities.

As seen in Figure 8, we find that the flux varies over the evolution of the flare. However, our fitting results suggest that the column density does not seem to vary significantly and is consistent, within uncertainties, with the Galactic column density along the line of sight ($3.49 \times 10^{20}$ cm$^{-2}$, HI4PI Collaboration et al. 2016). To determine whether the variability in the flux that we observe is intrinsic or is the result of a degeneracy between column density and photon index that can occur when analyzing low signal to noise data, we perform an additional fits of our spectra. Starting from our best-fit models, first we freeze the column density and refit the power-law model. We find that freezing the column density to our best-fit values does not change the photon index from our best-fit power-law model significantly. Similarly, we freeze our best-fit power-law model and let the column density be free. Again, we find that the derived column density is consistent with what we derived from our best-fit models when the column density, photon index, and normalization were set free. This suggests that the variability that we observe is intrinsic to the source.

The X-ray light curves and their hardness ratios are compared to the UV/optical light curves in Figure 2 and the aligned light curves are shown in Figure 3. The X-ray luminosity follows the previously observed trends. The X-ray luminosity consistently has a minimum $\sim$5 days before the optical peak but the depth of the minimum is variable. The largest decreases were for Flare 17 and Flare 18, and the smallest decrease was for Flare 19.

Near the minimum, the hardness ratio (HR) also changes. During quiescence before the flares, the HR is $\sim$ 0.5 and it

Figure 7. Continuum subtracted Si IV, C IV, C III], and Mg II profiles from the HST/STIS UV spectra. The black lines show the spectra, the red lines show the best fitting Gaussian profiles, and the blue, purple, green, and cyan dotted lines indicate the best fitting components of those profiles for C IV.
then hardens to HR $\sim$0.1–0.5 at the minimum. There was only a secondary X-ray minimum at +10 days in Flare 17. This secondary minimum also had a harder spectrum with HR $\sim$0.25. This “softer when brighter, harder when fainter” behavior is illustrated in Figure 9. Across all flares, both the hard and soft X-ray luminosities dip together, as shown in Figure 10, but the soft X-rays consistently nearly disappear completely during the minimums. Flare 19 was unusual in that both the total X-ray and soft X-ray luminosity were unusually bright when compared to the other flares. This indicates that the X-rays were uncharacteristically bright when the UV spectra were observed at $-12$ and $-9$ days relative to Flare 19’s optical peak. Overall, Figure 10 shows that ASASSN-14ko’s evolution is strongest in the softest energy band.

5.2. X-Ray Spectra from Chandra

Due to the spatial resolution of Swift XRT and NICER, it was not possible to separately analyze the X-ray properties of the two AGN nuclei present in ESO 253–G003. As shown by the contours in Figure 11, Chandra detects the two nuclei as separate sources coincident with the two nuclei identified by Tucker et al. (2021) in the optical.

We extracted X-ray spectra for both sources for the two epochs observed at +4 and +26 days relative to Flare 18’s g-band peak. For both epochs, the absorbed power-law xspec model tabls $\times$ zashift $\times$ power law with a photon index of 1.34 $\pm$ 0.11 at +4 days and 1.32 $\pm$ 0.09 at +26 days provided the best fit for ASASSN-14ko. These two spectra and the models are shown in Figure 11. A comparison of these two spectra indicates that the northern nucleus was brighter at +4 days during the UV/optical light curve decline versus at +26 days. We also extracted spectra for the southern nucleus at each epoch but found that the fit was not well constrained. The merged spectrum combining both epochs was best fitted as an absorbed power law with a photon index of 1.61$^{+0.56}_{-0.51}$, as shown in Figure 11. The spectral properties are summarized in Table 4. The Fe K$\alpha$ line seen in the archival XMM-Newton and NuSTAR observations (Payne et al. 2021) originates from the southern nucleus and not from ASASSN-14ko.

6. Discussion

We observed four of the most recent flares from ASASSN-14ko from X-ray through optical wavelengths. At the time of ASASSN-14ko’s discovery as a periodic transient, ASAS-SN had observed 16 flares over six years in the optical. Now, six
Figure 8. Representative binned NICER (left) and merged Swift (right) X-ray spectra with the best-fit models (solid lines) and the corresponding background spectra (dashed lines).
sequential flares have been observed at X-ray, UV, and optical wavelengths.

The six flares are UV dominated and have the blackbody SEDs typical of TDEs but with possible deviations going into the optical. They have different peak luminosities, indicating that the source is evolving, which was not clear from the lower quality ground-based light curves. The high-cadence TESS data further show that the optical flares do differ in terms of the peak luminosity and rise/decline morphology, but the changes were more subtle than in the UV. Flare 20’s much fainter UV flux and flatter evolution indicate that the UV properties can vary widely. It remains to be seen if this was a unique or particularly rare event.

Detecting these differences is important for understanding the physical nature of the system. For example, Payne et al. (2021) argued against interpreting the flares as being due to a star passing through and disrupting the SMBH accretion disk because the even and odd flares (i.e., up/down through the disk) were indistinguishable given the quality of the data. Thus far, the six flares observed in the UV also do not have any obvious differences between even and odd flares.

For the TDE hypothesis, the flares have to evolve, and the flares have to eventually (~100 yr based on \( P_0 = 115.2^{+1.3}_{-1.2} \) days and \( \dot{P} = -0.0026 \pm 0.0006 \)) come to an end. In this scenario, the envelope of a giant star is steadily being stripped at each pericentric passage. This means that the star has to evolve and the amount of mass stripped should change with time, both secularly and stochastically. The orbit should change with each pericentric passage, but it should not be completely regular—the period derivative should vary, and we may see evidence for this in our inability to fit all the peak times with a single \( \dot{P} \) (see Figure 1). Recent theoretical work on modeling ASASSN-14ko has also supported the partial TDE hypothesis. Cufari et al. (2022) used analytic arguments and three-body integrations to show that the Hills mechanism can result in the capture of a star on an orbit similar to ASASSN-14ko’s observed period. Metzger et al. (2022) proposed ASASSN-14ko as a system of two stars co-orbiting on an extreme mass ratio inspiral (EMRI), resulting in a long-lived mass-transfer.

King (2022) propose that ASASSN-14ko is caused by a white dwarf of mass \( 0.58M_\odot \) on 114 days orbit but the tidal disruption radius of a white dwarf is deep inside the event horizon given the black hole mass estimates. Finally, Liu et al. (2023) applied a theoretical framework of TDEs on elliptical orbits on ASASSN-14ko and found that putting a star on an elliptical orbit results in an unexpectedly reduced flare timescale, which would explain why ASASSN-14ko evolves faster than normal TDEs, both in its light curve and spectral features. In addition, Liu et al. (2023) found that the star has to be an evolved one with a massive core and an extended envelope based on the evolution of the luminosity, which is consistent with our findings.

The strong UV spectral evolution is notable not only for the remarkable evolution of the broad absorption lines but also for the extremely rapid timescale over which the line profiles changed. Compared to the UV spectra of both TDEs and AGNs, ASASSN-14ko’s UV spectra change in days versus the timescales of months or years observed for normal TDEs and changing-look AGNs. The general trend of the UV lines is the formation of a strong blue absorption feature at \( \sim -5000 \) km s\(^{-1}\) relative to the expected rest-frame central wavelength that appears prior to the optical peaks, which then vanishes and only a broad emission line around the rest-frame wavelength remains. This trend is most apparent for the C IV line, which shows the start of the formation of the blue absorption feature at \(-9\) days and evolves into an emission line by \(+7\) days. All of the absorption features are deep but they are not saturated. For Si IV at \(-4\) days, the line absorbs 17% of the continuum flux at maximum depth and 68% for C IV at \(-4\) days. This implies that the absorbing material must both have a high optical depth and a high covering fraction. Speculatively, if the \(-12\) days and \(-9\) days spectra represent the AGN UV emission which is unchanging during the flare, then we can subtract these from the \(-4, 0 \) and \(+7\) days flaring spectra (as shown in Figure 13). We then find that the C IV and Si IV absorption is optically thick in the core of the line.

We compare the UV spectra during ASASSN-14ko’s UV rise at \(-4\) days and quiescence at \(-36\) days to the UV spectra of TDEs, AGNs, and superluminous supernovae (SLSNe) in

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**Figure 9.** The connection between the hardness ratio evolution and the X-ray luminosity for all ASASSN-14ko flares observed with Swift XRT and NICER.
Figure 12. The UV continuum of ASASSN-14ko at $-4$ days most closely resembles the TDEs rather than the AGNs, which have consistently flat continua from the FUV to the NUV. There are no similarities between ASASSN-14ko and SLSNe.

Overall, ASASSN-14ko at $-4$ days most closely resembles iPTF15af because both objects have broad N V, Si IV, and C IV absorption features at similar velocities, along with a blue continuum. ZTF19abzrhgzq also showed broad absorption features at similar velocities.
features around these lines but at much higher velocities of \( \sim 15,000 \text{ km s}^{-1} \) (Hung et al. 2021). However, CIV and SiIV in ASASSN-14ko appear similar to classic P Cygni profiles, which are not apparent in any other TDE spectra. In comparison, the spectrum at \(-36\) days is dominated by emission lines akin to AGNs. The strong broad absorption features observed at \(-4\) days but not at \(-9\) days could either indicate that the feature only forms several days before the optical peak or that they only form when the X-ray luminosities reach a very low state, such as in Flare 18.

The MgII emission line is typically present in AGNs and comes from a partially ionized region (e.g., Peterson 1993; Richards et al. 2002). TDEs generally lack MgII emission, including ASASSN-14li, iPTF15af, iPTF16fnl, and possibly ASASSN-18jd. MgII was detected in absorption in ZTF19abzrhgq, but Hung et al. (2021) attributed this feature to the host ISM and circumnuclear gas instead of stellar debris associated with the TDE. In ASASSN-14ko, MgII is not strongly detected at \(-4\), \(+0\), and \(+7\) days but it is clearly detected at \(-36\) days. This trend is another instance of the UV spectra looking more TDE-like during the flares and more AGN-like during quiescence. Since MgII originates in partially ionized regions, the development of a luminous hard continuum should suppress MgII emission. The MgII line is always blueshifted from its expected rest-frame wavelength, which is likely to be a result of the host galaxy dynamics; as was also discussed in Tucker et al. (2021).

Figure 14 tries to place the various radii and velocities in context given the rough estimates of the SMBH mass from Payne et al. (2022), the Roche limits for main-sequence stars, here illustrated by an \(0.3M_\odot\) dwarf and...
the Sun, are very close to the Schwarzschild radius. Giants, which are illustrated using a star with a radius of $10R_\odot$, have Roche limits well outside the horizon. The apparent orbital period corresponds to a semimajor axis that is roughly 10 times larger than the Roche limit of such a star, which would be consistent with a star on an elliptical orbit being periodically stripped at pericenter. Note that a much larger star ($\sim 100R_\odot$) would be inconsistent with this picture because its Roche limit would be very similar to the semimajor axis. The range of blackbody radii shown in Figure 4 corresponds to a scale that is very similar to the Roche limit of the $10R_\odot$ star.

If we interpret the expansion of the blackbody radius from $10^{14.2}$ to $10^{14.9}$ cm over 8 days as a physical motion, then this implies a velocity of 34,000 km s$^{-1}$. As a circular velocity, this corresponds to a radius that is modestly larger than the blackbody radius and the giant Roche limit, and modestly smaller than the semimajor axis. The typical absorption and emission line velocities of $\sim 5000$ km s$^{-1}$, again interpreted as a circular velocity, correspond to radii an order of magnitude larger than the semimajor axis. The orbital timescales at these radii are decades, so the changes in the emission and absorption lines during a flare cannot be driven by physical motions associated with the flare—they must be due to ionization changes driven by changes in the luminosity and spectrum during the flare. The light travel times to these radii are several days to a week, so it should be possible to use intensive UV spectral monitoring during a flare to make a reverberation mapping measurement of the characteristic distance of the emission lines (absorption lines, by definition, have zero lag).

The six flares with X-ray observations are all characterized by an X-ray luminosity dimming and spectral hardening a few days before the optical peak. The column density does not change significantly, which rules out the possibility that the change in X-ray luminosity and spectrum is driven by a change in the absorption. ASASSN-14ko’s X-ray/UV/optical behavior is similar to ASASSN-18el (AT2018zf; Nicholls et al. 2018), which underwent a drop in X-ray luminosity by several orders of magnitude following the UV/optical brightening (Trakhtenbrot et al. 2019b; Ricci et al. 2020, 2021). Several scenarios have been advanced to explain ASASSN-18el’s behavior. It could be driven by an instability within the AGN accretion disk that causes a change in the accretion rate (Trakhtenbrot et al. 2019b) or an inversion of magnetic flux in a magnetically arrested disk (Scepi et al. 2021; Laha et al. 2022). Alternatively, ASASSN-18el was a TDE that destroyed the X-ray corona and inner accretion disk (Ricci et al. 2020, 2021) leading to the decreased X-ray luminosity and increased UV/optical emission. The X-ray luminosity then recovers as the X-ray corona reforms, and has most recently returned to its pre-outburst quiescence state as its X-ray luminosity steadily declined and spectrum hardened (Masterson et al. 2022). However, there are differences between these two objects, most notably that for ASASSN-18el the X-ray spectrum became softer rather than harder as it faded. The fading also occurred long after the optical peak and lasted for hundreds of days longer in ASASSN-18el. In addition, there were no X-ray observations taken at the same time as the optical peak, so it is not possible to make a direct comparison in terms of the X-ray behavior at optical peak, like for ASASSN-14ko. However, overall these two objects form a family of transients with unusual X-ray behavior.

### 7. Conclusion

ASASSN-14ko is a predictable nuclear transient whose flares are well-characterized by a timing model, although the individual flares are not identical. They do not, however, show an even/odd dichotomy, which we might expect from a star disrupting an accretion disk. Using ASAS-SN, Chandra, HST/STIS, NICER, Swift X-ray/UVOT, and TESS, we presented the photometric and spectroscopic X-ray/UV evolution and photometric optical evolution. Our findings can be summarized as follows:

1. We refit the timing model first used in Payne et al. (2021) to include the recent flare events and find period $P_0 = 115.2^{+1.3}_{-1.2}$ days and period derivative $P = -0.0026 \pm 0.0006$.

2. The UV and optical light curves always brighten to a single large-amplitude peak, but the peak luminosity varies between peaks. The UV luminosity peaks show larger differences than the optical luminosity peaks. This is also reflected in the blackbody luminosities.

3. The two TESS light curves from Sectors 3–5 and 31–33 show that the optical flares are not truly identical. The earlier flare began to rise earlier but more slowly to a fainter peak and then declined more slowly.

4. The X-ray luminosity consistently decreases during the UV/optical rise, but the depth of the minimum varies. Across all flares, the X-ray emission is consistently harder when fainter and softer when brighter. There seems to be no associated change in the absorption.

5. The Chandra data showed that the northern nucleus of the host galaxy brightened during the flare, indicating that this nucleus is the source of ASASSN-14ko’s X-ray emission. For both epochs, the absorbed power-law $xspec$ model $tbabs \times zashift \times$ power law with a photon index of $1.34 \pm 0.11$ at $+4$ days and $1.32 \pm 0.09$ at $+26$ days provided the best fit for ASASSN-14ko.

6. Both the UV continuum and UV spectral lines changed rapidly during Flare 18, as revealed by HST/STIS. The
Figure 12. Comparison of the HST/STIS UV spectrum of ASASSN-14ko taken four days prior to Flare 18’s optical peak to other UV spectra. The top panel shows the TDEs iPTF15af (Blagorodnova et al. 2019), ZTF19abzrhhgq (Hung et al. 2021), PS18kh (Hung et al. 2019), iPTF16fni Brown et al. (2018), and ASASSN-14li (Cenko et al. 2016). The middle panel shows the composite QSO spectrum of Vanden Berk et al. (2001), the nitrogen rich QSO SDSS J164148.19 + 223225.2 (Batra & Baldwin 2014), the ambiguous nuclear transient (ANT) ASASSN-18jd (Neustadt et al. 2020), and the AGN Mrk 817 (Kara et al. 2021). The bottom panel shows the superluminous supernovae Gaia16apd (Yan et al. 2017) and Gaia17biu (Yan et al. 2018). All of the spectra are normalized and offset for visibility. The ordering of the spectra relative to ASASSN-14ko is qualitative. The geocoronal airglow emission in each spectra is masked.
UV spectral lines that evolved the most dramatically were Ly$\alpha$, N V, Si IV, and C IV, which showed broad absorption features at $\sim 5000$ km s$^{-1}$ four days before the optical peak, which then vanished and were replaced by broad emission lines by seven days after peak. Overall, the UV spectra show some similarities to other UV TDE spectra during outburst but they are more similar to AGN spectra in quiescence.

We are continuing to monitor the flares and have proposed to obtain more complete UV spectra phase coverage. We have an extensive body of optical spectra and these will be analyzed in A. V. Payne et al. (2023, in preparation).

Acknowledgments

We thank the anonymous referee for their helpful and constructive comments. We thank Rick Pogge for the valuable discussions. We thank Las Cumbres Observatory and its staff for their continued support of ASAS-SN. ASAS-SN is funded in part by the Gordon and Betty Moore Foundation through grants GBMF5490 and GBMF10501 to the Ohio State University, and also funded in part by the Alfred P. Sloan Foundation grant G-2021-14192. A.V.P. acknowledges support from the NASA Graduate Fellowship through grant 80NSSC19K1679. B.J.S., C.S.K., and K.Z.S. are supported by NSF grant AST-1907570. B.J.S. is also supported by NSF grants AST-1920392, AST-1911074,
Appendix

In addition to emission and absorption features detected at the redshift of the host, the UV HST/STIS spectra exhibit low- and high-ionization absorption lines at $z=0$. We attribute these features shown in Figure 15 as originating from the Milky Way interstellar medium (ISM). These transitions consist of low-ionization elements (ionization energy $<13.6$ eV) N I, Si II, Lyα, C II, Fe II, Mg II, Al II, and O I, in addition to high-ionization elements (ionization energy $>13.6$ eV) S III, Si IV, and C IV. Numerous lines are affected by neighboring absorption and emission lines, but all absorption lines from the Galactic ISM are less than 500 km s$^{-1}$.

![Figure 15.](image.png)

Figure 15. Low- and high-ionization absorption lines attributed to the Milky Way ISM shown for the quiescence spectrum observed on 2021 March 6. The velocity scale is at rest-frame wavelength at $z=0$ for each line, or in the case of blended or doublet lines, an average of the two rest-frame wavelengths. Each velocity is indicated by the vertical-dashed lines. The shaded blue regions are areas of the spectrum affected by neighboring absorption and emission lines. The gray shaded regions show the spectrum uncertainty.
