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X-Ray, UV, and Radio Timing Observations of the Radio Galaxy 3C 120

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Abstract

We report the results of monitoring of the radio galaxy 3C 120 with the *Neil Gehrels Swift Observatory*, Very Long Baseline Array, and Metsähovi Radio Observatory. The UV-optical continuum spectrum and R-band polarization can be explained by a superposition of an inverted-spectrum source with a synchrotron component containing a disordered magnetic field. The UV-optical and X-ray light curves include dips and flares, while several superluminal knots appear in the parsec-scale jet. The recovery time of the second dip was longer at UV-optical wavelengths, in conflict with a model in which the inner accretion disk (AD) is disrupted during a dip and then refilled from outer to inner radii. We favor an alternative scenario in which occasional polar alignments of the magnetic field in the disk and corona cause the flux dips and formation of shocks in the jet. Similar to observations of Seyfert galaxies, intra-band time lags of flux variations are longer than predicted by the standard AD model. This suggests that scattering or some other reprocessing occurs. The 37 GHz light curve is well-correlated with the optical-UV variations, with a ~ 20 day delay. A radio flare in the jet occurred in a superluminal knot 0.14 milliarcseconds downstream of the 43 GHz “core,” which places the site of the preceding X-ray/UV/optical flare within the core 0.5–1.3 pc from the black hole. The inverted UV-optical flare spectrum can be explained by a nearly monoenergetic electron distribution with energy similar to the minimum energy inferred in the TeV γ -ray emitting regions of some BL Lacertae objects.

Key words: accretion, accretion disks – galaxies: active – galaxies: individual (3C 120) – radio continuum: galaxies – ultraviolet: galaxies – X-rays: galaxies

Supporting material: data behind figure

1. Introduction

The connection between the accretion disk (AD) and the jets of active galactic nuclei (AGN) is a key aspect of our physical picture of how these extremely energetic objects operate. There are, however, only a small number of AGN with luminous, relativistic jets where emission from the inner AD plus corona of hot electrons is not overwhelmed by nonthermal emission from one of the two jets. One of these is the Fanaroff–Riley 1 (FR 1) (Fanaroff & Riley 1974) radio galaxy 3C 120 ($z = 0.033$). The mass of the central black hole in 3C 120, as determined from time delays between variations in the optical continuum and emission-line fluxes (“reverberation mapping”), combined with the virial theorem, is $5.6 \pm 0.5 \times 10^7 M_\odot$ (Bentz & Katz 2015). This mass is similar to that obtained from comparing the break in the X-ray power spectral density to that of Cygnus X-1 (Chatterjee et al. 2009; Marshall et al. 2009). Previous *Rossi X-ray Timing Explorer* and Very Long Baseline Array (VLBA) observations of 3C 120 have revealed that the emergence of an apparently superluminal radio knot in the jet is preceded by a dip in the X-ray flux (Marscher et al. 2002; Chatterjee et al. 2009). Persistent Fe K α emission lines in the X-ray spectrum of 3C 120 (e.g., Eracleous et al. 2000; Ogle et al. 2005) imply that the bulk of its X-ray emission originates in the AD-corona system. Observations of nine such dip-ejection events and a similar X-ray spectrum in the FR 2 radio galaxy 3C 111 (Chatterjee et al. 2011) suggest that the behavior is a general characteristic of radio galaxies.

At radio frequencies, 3C 120 possesses blazar-like characteristics: variability on timescales of weeks to years and a one-sided parsec-scale jet with bright superluminal knots ejected 2–6 times per year at apparent speeds of 3–9c (Gómez et al. 2001a; Jorstad et al. 2005, 2017; Chatterjee et al. 2009; Casadio et al. 2015). The mean time delay of 68 ± 14 days between X-ray dips and the passage of superluminal knots through the 43 GHz “core” (nearly unresolved, bright emission feature at the upstream end of the jet in 43 GHz VLBA images) in 3C 120 indicates that the core lies ~ 0.5 –1 pc from the corona (Marscher et al. 2002; Chatterjee et al. 2009) and is probably a standing shock in the jet.

While the temporary drop in X-ray flux followed by the appearance of a superluminal radio knot in the jet suggests that radio galaxies and black hole X-ray binary systems (Fender et al. 2004) behave in a similar fashion, there are important differences, as noted by Chatterjee et al. (2009) and Punsly et al. (2015). The inner AD surrounding a supermassive black hole, as in 3C 120, is not hot enough to emit X-rays. Rather, the emission from the AD is at UV and longer wavelengths. The primary X-rays therefore originate in the corona of hot electrons, which scatters optical-UV photons emitted by the AD up to X-ray energies (e.g., Fabian et al. 2015, 2017). In the standard model, some of these X-rays penetrate into the AD, where they are re-processed to produce the “reflection” spectrum that includes the Fe K α line (e.g., Ogle et al. 2005; Lohfink et al. 2013) and UV-optical continuum (e.g., McHardy et al. 2014; Gardner & Done 2017).

Two distinct models have emerged to explain the observed X-ray/radio link in 3C 120. Lohfink et al. (2013) have suggested that the jet–disk connection occurs via a jet cycle similar to that of X-ray binary systems. The cycle consists of four stages: (1) full AD; (2) disappearance of the innermost regions of the AD and ejection of matter out of the disk plane, causing an X-ray and UV-optical dip; (3) mass–energy ejection along the jet, resulting in a radio flare and the formation of a new superluminal knot; and (4) refilling of the AD from outer to inner radii. Under a model by Chatterjee et al. (2009), the bulk of the optical emission in 3C 120 is generated in the AD, while most of the X-ray continuum is produced by scattering in the corona of mainly UV radiation emitted by the AD. In this model, the corona is actually the base of the jet, very close to the black hole, as proposed for X-ray binaries (Markoff et al. 2005) and AGN (King et al. 2017). An increase in the speed of flow through the base lowers the density of Compton-scattering electrons, causing a dip in the X-ray flux while sending a shock wave down the jet. The shock becomes visible in VLBA images ~ 2 months later as a superluminal knot emerging from the core.

The Lohfink et al. (2013) model predicts that the UV continuum should drop along with the X-rays during a flux dip, and then recover first at longer and then at shorter wavelengths. The decrease in UV flux should occur slightly ahead of the start of the X-ray decline. Under the Chatterjee et al. (2009) model, the UV-optical flux should decline after the X-ray dip starts, if the temperature of the UV-optical emitting region changes in response to the lower X-ray flux. In order to test these predictions, we carried out a nine-month campaign of monitoring observations of 3C 120 with the X-Ray Telescope (XRT) and UV-Optical Telescope (UVOT) of the Earth-orbiting *Neil Gehrels Swift Observatory* (hereafter, *Swift*). In order to monitor changes in the relativistic jet, we imaged 3C 120 with the VLBA at 43 GHz as part of the VLBA-BU-BLAZAR program (Jorstad & Marscher 2016). Here, we present and interpret the resulting multi-band X-ray, UV, and optical light curves, at a cadence of 2–3 observations per week, as well as roughly monthly VLBA images of 3C 120. Section 2 describes the observations and data reduction procedures, Section 3 presents the results of the observations, and Section 4 discusses and interprets the results. We summarize our conclusions in Section 5.

2. Observations and Data Analysis

2.1. X-Ray

Swift observed 3C 120 approximately three times per week between 2016 July 14 and 2017 March 27 with the XRT over a photon energy range of 0.3–10 keV. Most of the observations were in Window Timing mode in order to avoid pileup of photons in individual pixels in between data readouts. We processed the data with the standard HEASoft (Arnaud 1996) package [versions 6.19 (2016 data) and 6.21 (2017 data)], using the task `xrtpipeline` to identify times of acceptable data quality and to calibrate the data. This included examination of the path of 3C 120 across the detector, which led to the exclusion of a small number of observations during which 3C 120 was outside the field over $\geq 50\%$ of the exposure time. We created an ancillary response file with correction for the point spread function via task `xrtmkarf`, and then rebinned the data with task `grppha` in order to include at least 20 photons in each energy channel. We used XSPEC

(Arnaud 1996) to fit the spectra with a single power-law model, setting the neutral hydrogen column density to a fixed Galactic value of $1.11 \times 10^{21} \text{ cm}^{-2}$ (Dickey & Lockman 1990). We employed the Monte Carlo method in XSPEC to determine the goodness of the fit at each epoch. A χ^2 per degree of freedom less than 2 was required to consider the fit to be acceptable. Uncertainties in the spectral index, normalization, and integrated flux are given at the 90% confidence level.

Lohfink et al. (2013) fit the X-ray spectrum of 3C 120 with a model that includes a power-law soft-excess component. We can place a limit on the level of such a soft excess in our *Swift* spectra by adding a second power-law component and determining how high its flux could be without degrading the χ^2 of the fit to the data to a statistically unacceptable value. Lampton et al. (1976) determined that, for three adjustable parameters, an increase in the χ^2 by 11.3 from the best-fit value allows one to reject a spectral model at the 99% confidence level. We fit the X-ray spectra from four epochs during relatively quiescent periods of the X-ray light curve with the double power-law model. We set the power-law photon index of the tentative soft-excess spectrum to 2.5—the lowest value derived for the Lohfink et al. (2013) spectral fits (which minimizes the disagreement with our data)—and allowed the spectral index of the main power-law component, as well as the flux normalizations of both components, to vary. Adding the soft excess component did not improve the fit at any of the epochs. We found that the maximum allowed normalization of the soft excess is $3 \times 10^{-3} \text{ photons keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$, about half of the lowest value in the Lohfink et al. (2013) model.

2.2. Ultraviolet and Optical

Simultaneous with the XRT observations, fluxes were measured in the UVW2 (central wavelength of 192.8 nm), UVM2 (224.6 nm), UVW1 (260.0 nm), U (346.5 nm), and V (546.8 nm) bands of the *UVOT* onboard *Swift*. We incorporated the current (at the time of data processing) version of the calibration files with the current version of the HEASoft package to reduce the data. Fluxes were extracted over an aperture of radius $5''$ after subtraction of the background flux measured within a source-free region of radius $20''$. We summed all exposures composing each image with `uvotimsum`, and processed the data with `uvot-source` with parameter $\sigma = 5$. Five of the UVOT fluxes thus derived were isolated outliers, with the UVW2 flux lower than contiguous points by 30–50% and fluxes at the other bands lower by smaller fractions. Similar outliers have been investigated by Gelbord et al. (2015), who determined that they are caused by bad pixels on the CCD. Therefore, we have excluded the outliers from our data set.

We supplement the *Swift* data with I, R, V, and B band fluxes and linear polarization measured with the 1.83 m Perkins Telescope of Lowell Observatory in Flagstaff, AZ. The data acquisition, reduction, and analysis procedures are described by Jorstad et al. (2010). The polarization is corrected for the interstellar value of $1.22 \pm 0.06\%$ in position angle $98^\circ \pm 1^\circ$, as determined from observations of three comparison stars in the field, which we assume to be intrinsically unpolarized.

We apply corrections for interstellar extinction with values from Schlafly & Finkbeiner (2011) listed in the NASA Extragalactic Database (NED) for the I, R, V, B, and U filters. For the UV data, we adopt the interstellar extinction curve of

Fitzpatrick (1999) with $R_V = 3.1$. The values of extinction thus derived are $A_\lambda = 0.448, 0.645, 0.816, 1.079, 1.289, 1.734, 2.412$, and 2.132 for the I, R, V, B, U, UVW1, UVM2, and UVW2 bands, respectively.

2.3. Light Curve at 37 GHz

The 13.7 m radio telescope at Aalto University Metsähovi Radio Observatory includes 3C 120 in its regular monitoring program, measuring its millimeter-wave flux density multiple times per month during the period covered by the current study. The observations utilized a 1 GHz band dual beam receiver with a central frequency of 36.8 GHz. Flux densities are calibrated by observations of DR 21, with NGC 7027, 3C 274, and 3C 84 serving as secondary calibrators. A detailed description of the data reduction and analysis is given in Teräsanta et al. (1998).

2.4. Millimeter-wave VLBA Imaging

Since early 2012, we have routinely (roughly once per month) observed 3C 120 with the VLBA under the VLBA-BU-BLAZAR monitoring project. Each 24 hr session includes 40–48 minutes of observations of 3C 120, split into 10–13 scans of 3–5 minute durations. After correlation of the data from the ten antennas with the DiFX software correlator at the Long Baseline Observatory site in Socorro, New Mexico, we calibrate the data with the Astronomical Image Processing System (AIPS) software provided by the National Radio Astronomy Observatory. We then use Difmap (Shepherd 1997) to perform imaging and self-calibration through an iterative procedure. This involves making a preliminary image that is then used in the Astronomical Image Processing Software (AIPS) (van Moorsel et al. 1996) routine CALIB, which independently adjusts the left and right circularly polarized visibility phases, guided by the image, before final imaging and self-calibration in Difmap. Calibration of the electric-vector position angle χ of the linear polarization is based on the multi-faceted approach of Jorstad et al. (2005). Jorstad et al. (2017) list further details of the data analysis procedures.

In order to quantify the emission structure in the jet, at each epoch we use the Difmap model fitting procedure to divide the source into a number of emission components, each with a circular Gaussian intensity distribution. The starting model is the best-fit model of the previous epoch. The model fit determines the position relative to the core, flux density, and full width at half maximum (FWHM) angular size of each component. Jorstad et al. (2017) discuss the uncertainties in the model-fit parameters.

3. Results

3.1. Light Curves

Figure 1 presents the *Swift* X-ray light curves, with the unsmoothed 0.3–10 keV data in the top panel, and smoothed 0.3–10 keV, 2–10 keV (hard X-ray), and 0.3–2 keV (soft X-ray) data in the next three panels. The bottom panel displays the smoothed spectral index α , where the flux density $F_\nu \propto \nu^{-\alpha}$. The smoothing is over five consecutive points, with the flux at the epoch of the data point assigned 40% weight, contiguous points given 20% weight, and points two epochs earlier or later given 10% weight. (The first and last data points are not smoothed, while the second and penultimate

Figure 1. Light curves of 3C 120 and (bottom panel) energy spectral index from *Swift* XRT observations over the indicated X-ray energy ranges. Except for the top panel, the values plotted are smoothed over five consecutive observations (see text). The data used to create this figure are available.

are smoothed over three epochs.) The smoothed data facilitate visual comparison with the UV and optical light curves, whose characteristic timescales of variation are longer than that of the X-ray flux. However, in the correlation analysis below, we use the unsmoothed values.

Figure 2 displays the UV and optical light curves of 3C 120, along with the smoothed 0.3–10 keV X-ray data. Minima in the light curves (“dips”) are denoted by red vertical dashed lines and numbered for reference. In order to be classified as a dip, the minimum in flux needs to be apparent at all bands. The local minimum near MJD 57760 is not included because the flux exceeds the mean flux in the UV-optical bands, and the minimum appears to be part of a double-flare outburst rather than a dip as defined by Chatterjee et al. (2009). Figure 3 expands the portions of the light curves that include dips 1 and 2.

The top panel of Figure 4 presents the 37 GHz light curve of 3C 120 during our *Swift* monitoring campaign, as well as during the previous year. The earlier data include the highest-amplitude millimeter-wave outburst ever observed in 3C 120. In Section 4.4, we compare the multi-waveband behavior during this event with that of the strong outburst in 2017. For comparison, the V-band optical light curve is also displayed, as are the R-band degree (P) and electric-vector position angle (χ) of linear polarization. There is a V-band counterpart to each radio flare.

3.2. Changes in the Jet

Figure 5 presents a time sequence of 16 VLBA images at a frequency of 43 GHz from 2016 June to 2017 August. The angular resolution of the longest baselines is ~ 0.1 mas along

Figure 2. Smoothed 0.3–10 keV X-ray and unsmoothed UV-optical light curves of 3C 120 from *Swift* observations. Three minima in the light curves are marked as “dips” with red vertical dashed lines, a flare is indicated by a vertical dashed line, and epochs t_0 when a superluminal knot passed the “core” of the jet, as seen in 43 GHz VLBA images, are denoted by upward arrows in the bottom panel. The uncertainty in each epoch is denoted by a horizontal line. The photometry shown in this figure is available as data (see Figure 1).

the direction of the jet. At a distance of 140 Mpc (for a Hubble constant of $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$), 0.1 mas corresponds to a length of 0.064 pc projected on the sky. For an angle θ between the jet and the line of sight ($\sim 10^\circ$ Jorstad et al. 2017), the deprojected conversion is $0.1 \text{ mas} = 0.36 (\sin 10^\circ / \sin \theta) \text{ pc}$. The “core” is the bright feature (A0 in Figure 5) at the eastern end of the jet, and is presumed to be stationary. In compact extragalactic radio sources, the properties of the parsec-scale core are consistent with those expected from a standing conical shock in the jet (Cawthorne 2006, 2013; Marscher 2014; Marscher et al. 2017). The images reveal a second quasi-stationary emission feature, A1, located 0.14 mas (0.51 pc for $\theta = 10^\circ$) downstream of the core. Figure 6 plots the separation of each knot from the core as a function of time (as determined by model fitting; see above), with a straight-line fit to the apparent motion. Extrapolation of the fit to zero separation yields the “ejection” time t_0 when the brightness centroid of each moving knot coincided with that of the core. Table 1 lists the apparent motions and values of t_0 for knots K1 to K6; there are insufficient data in Figure 6 to determine the motion of K7.

Figure 7 displays the 37 GHz flux density of the entire source versus time, along with the flux densities of the brightest individual emission features identified on the 43 GHz VLBA images. It is apparent that the maximum in flux density at MJD 57795 is mainly the result of increases in flux density of superluminal knots K3 and K4 when they were 0.17 and 0.25 mas, respectively, downstream of the core (see Figure 6).

3.3. Correlation Analysis

In order to relate the flux variations across the X-ray, UV, and optical bands, we use the z-transformed discrete correlation function maximum likelihood methods ZDCF (Alexander 1997) and PLIKE (Alexander 2013), which have been shown to determine correlations of unevenly sampled data effectively. In order to assess the statistical significance of the correlations, we create 3000 artificial light curves (ALCs) at each waveband by using the actual data points. As in Williamson et al. (2014, 2016), active periods are identified and randomly assigned start dates from the list of actual dates of observation. After this procedure, which preserves the structure of flares present in the light curves, the remaining observed fluxes are randomly assigned to vacant actual observation dates. The ALCs of the two wavebands being correlated are then randomly paired and processed with the ZDCF routine. A ZDCF value is considered to be statistically significant at the 95% level if its magnitude exceeds that of 95% of the artificial values. The flux redistribution/random subset selection method (Peterson et al. 1998) was also employed as a check on the ZDCF results. We found complete consistency between the two methods.

Figure 8 presents the cross-correlations of the *Swift* data. The hard (2–10 keV) and soft (0.3–2 keV) X-ray variations are well-correlated, as are the UV and optical bands. The correlation between the X-ray and UV variations, however, is more complex. As seen in the middle left panel in Figure 8, the X-ray/UVW2 correlation is moderately strong (peak ZDCF of 0.5) and flat from -12 days (X-ray leading) to zero. A non-zero lag over a ~ 40 day time span is apparent in the light curves exhibited in Figure 2, starting with the event designated “dip 2.” In order to determine whether this change in lag is statistically significant, we perform the correlation analysis separately on two halves of the light curves: from MJD 57550 to 57724, and from 57726 to 57850. The result is displayed in Figure 9. The ZDCF for the first time range peaks sharply at zero lag, with a somewhat lower maximum value of 0.41 (at least partly caused by the lower flux level, which increases the fraction of the flux contained in non-variable—or slowly varying—components, such as starlight from the host galaxy). In contrast, there is a maximum of 0.48 at -6 days and from -10 to -14 days for the second time interval, with less pronounced peaks of 0.31, 0.36, and 0.38 at lags of zero, -20 , and -26 days, respectively. All of these local maxima of the ZDCF are significant beyond the 95% level. The difference in the correlations between the first and second halves of our monitoring period implies that the multi-waveband behavior was more complex during the period of the double flare than during the previous, more quiescent period.

We determine the cross-wavelength time lags by calculating the centroids of the cross-correlations, calculated over the area above 80% of the maximum ZDCF value. We obtain

Figure 3. Expanded view of the light curves (without smoothing) over time spans that include dip 1 (left side) and dip 2 (right side). The red vertical dashed lines mark the epochs of minimum UVW2 flux, while the horizontal blue lines indicate the pre-dip flux level, obtained by averaging the three data points immediately preceding the corresponding dip. The photometry shown in this figure is available as data (see Figure 1).

the following lags, with negative lags corresponding to variations at the first waveband listed leading those at the second waveband. Hard/soft X-ray: -0.25 ± 0.68 days; X-ray(0.3–10 keV)/UVW2: -6.2 ± 2.4 days; UVW2/UVM2: -0.87 ± 1.0 days; UVW2/UVW1: -1.2 ± 1.0 days; UVW2/U: -3.3 ± 1.0 days; and UVW2/V: -1.4 ± 1.6 days. For the correlations during two separate time periods displayed in Figure 9, we find lags of: X-ray (0.3–10 keV)/UVW2: $+0.1 \pm 0.5$ days and UVW2/U: -1 ± 1 days over MJD 57550–57724, and X-ray (0.3–10 keV)/UVW2: -10 ± 3 days and UVW2/U: 3 ± 2 days for MJD 57726–57850. The lags between the X-ray and both UVW2 and U variations are consistent with those obtained by Buisson et al. (2017), whose uncertainties are higher owing to sparser time coverage.

3.4. Linear Polarization

The optical linear polarization measurements are plotted in the bottom two panels of Figure 4. Values range from ~ 1 to 2.2%, with uncertainties of ± 0.1 –0.2%. The electric-vector position angle χ lies within $\sim 45^\circ$ of the jet axis at all of the epochs. The VLBA images presented in Figure 5 indicate the polarized intensity and EVPAs at various locations in the parsec-scale jet. As has been the case at most earlier epochs (Gómez et al. 2001a, 2001b), polarization is not detected in feature A0 (the “core”) at any of the epochs. This could result from either Faraday depolarization or a highly disordered magnetic field. Stationary feature A1 is significantly polarized only at epochs when a superluminal knot passes through it. The

Figure 4. Top panel: light curve of 3C 120 at 37 GHz from measurements made at the Metsähovi Radio Observatory. Second panel from top: optical V-band light curve; bottom two panels: degree and electric-vector position angle of optical R-band linear polarization. The direction of the innermost jet in 43 GHz VLBA images is indicated in the bottom panel for comparison. The photometry shown in this figure is available as data (see Figure 1).

value of χ when this occurs is usually $\sim 90^\circ$, parallel to the inner jet direction and within $\sim 45^\circ$ of the optical EVPA.

4. Discussion

4.1. Modeling the UV-Optical Emission

The X-ray, UV, and optical light curves displayed in Figures 1 and 2 are characterized by major dips and flares, as well as apparently random, lower-amplitude fluctuations. (Three dips and the most pronounced flare at UV-optical wavelengths are marked in Figure 2.) This behavior is similar to that reported in 2002–08 by Chatterjee et al. (2009), although the X-ray and R-band quiescent flux levels are $\sim 20\%$ and $\sim 100\%$ higher, respectively, in 2016–17 relative to the average levels in 2002–08. During the relatively quiescent period of MJD 57683–57717, the error-corrected rms variability (see Buisson et al. 2017) after removal of a linear trend is V band: 0.81 ± 0.30 mJy ($14 \pm 5.2\%$), U band: 0.56 ± 0.20 mJy ($9.7 \pm 3.5\%$), UVW1 band: 0.42 ± 0.16 mJy ($7.4 \pm 2.8\%$), UVM2 band: 0.41 ± 0.16 mJy ($5.7 \pm 2.2\%$), UVW2 band: 0.52 ± 0.14 mJy ($6.7 \pm 1.9\%$), and X-ray (0.3–10 keV): $(8.1 \pm 3.0) \times 10^{-12}$ erg cm $^{-2}$ s $^{-1}$ ($14 \pm 5.2\%$). A least-squares straight line with $\alpha_{\text{rms}} = 0.48 \pm 0.22$ passes within 0.7σ of all of the UV-optical rms-variability data points, although the U, UVW1, and UVM2 measurements all lie below the line and the UVW2 value lies above. Buisson et al. (2017) measured a quite different slope for 3C 120, $\alpha_{\text{rms}} = -0.21 \pm 0.10$ in 2011–12, similar to their values for radio-quiet Seyfert galaxies. This implies a more significant steep-slope, variable UV-optical component in 3C 120 in 2016–17.

Between dips 2 and 3, the X-ray, UV, and optical light curves are dominated by a double flare. The top panel of Figure 10 displays the UV-optical spectrum on MJD 57655, a

date during a relatively quiescent period when we obtained data from all optical and UV bands listed in Section 2.2. The middle panel of Figure 10 presents the spectrum at the peak of the second flare on MJD 57783. (We have not subtracted the flux of emission lines or starlight from the host galaxy.) The spectrum at both epochs can be fit by a simple power law that is flatter during the flare, when the spectral index $\alpha = 0.46 \pm 0.03$, compared with the quiescent value of 0.71 ± 0.05 . The power laws are too steep and extend to frequencies too high to be explained by a superposition of blackbody emission from hot dust, starlight, and the AD, as found in several quasars (Kishimoto et al. 2008). Instead, the spectra are consistent with synchrotron radiation, at least at the longer optical wavelengths. In this case, the flattening of the UV-optical spectrum during the flare would correspond to an increase in efficiency of acceleration of electrons toward higher energies. This interpretation is consistent with the optical linear polarization of 1–2% measured during the *Swift* monitoring (see Figure 4), as is discussed in Section 4.4.

The zero lag between the X-ray and UV-optical variations during the quiescent period (see Section 3.3 and Figures 8 and 9) requires the UV emission region to lie within 0.5 light-days (the uncertainty in the peak lag value) of the X-ray source, and could be coincident with it. One possibility is that the X-ray and UV-optical emission both originate in the base of the jet, as has been proposed for X-ray binaries by Markoff et al. (2005). However, models for relativistic jet formation that rely on strong helical magnetic fields within $\sim 1000R_g$ of the base (e.g., Blandford & Znajek 1977; Blandford & Payne 1982; Vlahakis & Königl 2004; McKinney & Narayan 2007; Tchekhovskoy et al. 2011) predict a high degree of linear polarization unless the jet points within $\sim 2^\circ$ of our line of sight (Lyutikov et al. 2005), contrary to observations (see above; Jorstad et al. 2017).

An interpretation that explains various aspects of the data incorporates two main UV-optical emission components: an inverted-spectrum (IS) source plus a steep-spectrum synchrotron source. In order to assess whether the AD could be the IS source, we integrate the Planck function over radius to produce a thin-disk spectrum, and add a power-law nonthermal spectrum $F_\nu \propto \nu^{-\alpha}$ for both the quiescent and flaring states. The best-fit model, which is compared to the observed spectra in Figure 10, combines a synchrotron component with $\alpha = 1.2$ with an AD of inner radius $r_{\text{in}} = 1.3 \times 10^{13}$ cm ($1.6R_g$, where $R_g = GM/c^2$ is the gravitational radius for a black hole of mass M), outer radius $r_{\text{out}} \geq 1.3 \times 10^{16}$ cm (5.0 light-days), and temperature as a function of distance r from the black hole $T(r) = T_{\text{in}}(r/r_{\text{in}})^{-3/4}$. In the model, $T_{\text{in}} = 3.0 \times 10^5$ K at the quiescent epoch MJD 57655. The thermal component has an inverted UV-optical spectrum with the standard AD spectral index of $\alpha = -1/3$. In order to reproduce the flattening of the spectrum during the flare, we increase the flux of only the AD component by raising T_{in} by 33% to 4.0×10^5 K at the peak of the flare while keeping the synchrotron component constant. A smaller range of AD radii would result in curvature of the spectrum well beyond the observational constraint. A larger value of r_{in} would increase the flux by increasing the area of the disk at a given temperature, and would thus require a small area filling factor, $(1.3 \times 10^{13} \text{ cm}/r_{\text{in}})^2$, to match the observed flux level. The flare minus quiescent spectrum, displayed in the bottom panel of Figure 10, rises with frequency, and can be fit

Figure 5. VLBA images of 3C 120 at 43 GHz. Contours: total intensity in factors of 2 starting at 0.25% of the global peak of (left panel) 1.17 Jy beam⁻¹ (attained on 2016 October 6), and (right panel) 2.41 Jy beam⁻¹ (attained on 2017 February 4), with images at these two epochs including an extra contour at 95%. Color: linearly polarized intensity. Red line segments: electric-vector position angle of linear polarization. The “core” (A0), stationary feature A1, and superluminal knots (K_n) are indicated. The elliptical Gaussian restoring beam of FWHM dimensions 0.34×0.14 mas with major axis along position angle -10° is displayed in the bottom left corner of each panel.

by a power law with spectral index $\alpha = -0.28 \pm 0.07$, consistent with the theoretical value of $-1/3$. (Note that this difference spectrum subtracts any steady emission component such as starlight from the host galaxy.)

The value of T_{in} agrees roughly with the expectations of an AD model. When irradiated by a small (compared to the AD dimensions) X-ray source with luminosity L_x located at a height

h_x above the center of the disk, the model gives

$$T(r) \approx \left[\frac{3GM\dot{M}}{8\pi\sigma r^3} + \frac{(1-a)L_x h_x}{4\pi\sigma r_x^3} \right]^{1/4}, \quad (1)$$

(Cackett et al. 2007; Lira et al. 2011), where r_x is the distance between the X-ray source and disk at radius r (assumed to be

Figure 6. Separations from the “core” of emission features identified in the VLBA images of 3C 120 at 43 GHz. Moving knots identified in Figure 5 are coded in color and labeled. The horizontal colored bars denote the range of times ($\pm$ uncertainties) when the brightness centroid of the knot with the corresponding color was at the centroid of the core, as determined by a backward extrapolation of its motion.

Figure 7. Light curve of the entire source at 37 GHz along with the light curves at 43 GHz of individual emission components identified in the VLBA images. Flux densities of the components are derived from model fitting. At a given epoch, the sum of the individual flux densities may be less than that of the entire source because of errors in the VLBA flux calibration and/or model fitting, as well as emission from low-intensity features not included in the model fitting. The photometry shown in this figure is available as data (see Figure 1).

Table 1
Apparent Motions of Moving Knots

Knot	μ (mas yr ⁻¹)	v_{app} c	t_0 (MJD)	t_0 decimal yr
K1	2.27 ± 0.03	5.06 ± 0.07	57588 ± 5	2016.549 ± 0.015
K2	1.97 ± 0.05	4.84 ± 0.11	57705 ± 8	2016.830 ± 0.021
K3	1.60 ± 0.09	3.56 ± 0.20	57742 ± 9	2016.97 ± 0.03
K4	1.44 ± 0.13	3.17 ± 0.29	57757 ± 22	2017.01 ± 0.006
K5	2.32 ± 0.15	5.17 ± 0.33	57847 ± 11	2017.26 ± 0.03
K6	1.29 ± 0.29	2.88 ± 0.64	57855 ± 36	2017.28 ± 0.10

greater than h_x), M is the mass of the black hole and $\dot{M}$ is its accretion rate, L_x is the luminosity of the X-ray source, a is the albedo of the disk, and σ is the Stefan–Boltzmann constant. In the quiescent state of 3C 120, $L_x \approx 2 \times 10^{44} \text{ erg s}^{-1}$, where we have assumed a spectral index of 0.87 up to a cutoff energy of $\sim 100 \text{ keV}$ measured by NuSTAR at an earlier epoch (Rani & Stalin 2018), which is similar to the spectral indices derived from our *Swift* observations (see Figure 1, bottom panel). For the albedo, which is poorly known, we adopt $a \sim 0.2$. For the accretion rate, we estimate $\dot{M} \sim 0.013 M_\odot \text{ yr}^{-1}$ by dividing the quiescent value of the far-UV luminosity, $\sim 3 \times 10^{44} \text{ erg s}^{-1}$, by c^2 and by an assumed efficiency of 40% of conversion of accretion power into radiation for a rapidly spinning black hole (Shakura & Sunyaev 1973). The resulting value of T_{in} is $\sim 3 \times 10^5 \text{ K}$, in agreement with the value from our spectral model during quiescence. However, the increase in temperature of the AD by 33% in the spectral model of the flare exceeds the maximum possible increase (when the second term of Equation (1) dominates) of 10% resulting from an increase in X-ray luminosity by the observed flare:quiescent ratio of ~ 1.5 . A more complex, or different, model is therefore needed to explain the high-amplitude variations in UV-optical flux.

The level of fluctuations in flux during the quiescent period (see above) agrees with the two-component model. There is a minimum in the fractional flux variability in the UVW1 band, which is near the wavelength where the IS and synchrotron source contribute nearly the same fraction of the total flux density. If the synchrotron and IS fluctuations are unrelated, then they will often partially cancel each other near that wavelength, whereas the fluctuations are dominated by a single component—and therefore more coherent—at shorter and longer wavelengths. In the case of fluctuations corresponding to random noise, the sum of flux variations from two components with equal variability amplitude is expected to have an rms $\sim 1/\sqrt{2}$ times lower than that of a single component. The reduction in rms from the V band to UVM2 and increase from UVM2 to UVW2 during the relatively quiescent period (see above) agree with this expectation.

Qualitative support for the proposal that the AD is the IS source can be found in time lags of the multi-wavelength variability of the flux density. As seen in the top right panel of Figure 9, during the relatively quiescent period of MJD 57550–57724, the UVW2 variations lead the U-band variations by -1 ± 0.5 days, with peaks in the ZDCF at both 0 and -4 days. During the flaring period (bottom right panel of the figure), the ZDCF is broader, with a peak at -3 ± 1 days. This delay toward longer wavelengths is consistent with the AD model if variations in flux propagate from inner to outer radii at speeds $< c$. However, the longer UVW2/U delay relative to the UVW2/V lag is naturally explained as scattering via Balmer continuum emission by clouds a few light-days from the inner AD (Cackett et al. 2018). Furthermore, as is discussed in Section 4.3 below, cross-wavelength time lags $\gtrsim 0.5$ days are much longer than predicted by the basic AD model, which therefore needs additional features in order to explain all of the data.

The spectral index of the flare-minus-quiescent spectrum is also similar to the value of $-1/3$ for optically thin synchrotron radiation from electrons whose critical frequencies are all higher than $\sim 2 \times 10^{15} \text{ Hz}$ (see Pacholczyk 1970). The minimum energy of such an electron population would need to exceed $\sim 10B^{-1/2} \text{ GeV}$, where B is the magnetic field

Figure 8. ZDCF cross-correlations (normalized) of selected unsmoothed light curves as indicated in each panel. The hard X-ray photon energy range is 2–10 keV, while the soft X-ray range is 0.3–2 keV. The correlation functions are smoothed over three lag times, with 50% weight for the central time and 25% weight for each of the preceding and succeeding times. Negative lags correspond to the first waveband listed leading the variations. Dotted curves delimit the 95% confidence level. See the text for details.

strength in Gauss. The maximum energy could not be greater than ~ 3 times higher than the minimum. Otherwise, the soft X-ray synchrotron flux would exceed the observed value; cf. the spectral energy distribution (SED) during the flare, displayed in Figure 11. Such a sharply peaked SED is a possible outcome of particle acceleration by magnetic reconnection (see Petropoulou et al. 2016). In fact, models of very high-energy γ -ray emission from BL Lacertae objects—which are associated with FR 1 radio sources—generally require minimum energies of ~ 10 GeV (e.g., Balokovic et al. 2016). In Section 4.4 below, we find that this alternative model for the IS component during the flaring period is consistent with a strong correlation found between the UV-optical and 37 GHz variations of 3C 120.

4.2. Dips in Flux

As is discussed in Section 1, the inner-disk disruption scenario for 3C 120 proposed by Lohfink et al. (2013) predicts that, during dips in flux, the UV flux should decrease a short time before the X-ray flux. Because the inner disk is refilled from larger to smaller radii, the recovery of the flux to its pre-dip value should proceed from longer to shorter wavelengths at a propagation speed $v_{\text{refill}} \ll c$.

As seen in Figure 3, during dip 1 the UVW2 flux decreased by 15% prior to the first significant decrease (by about the same percentage) in the X-ray flux one observation (2.2 days) later. However, a pre-dip X-ray flare, which is also apparent in the UVM2 data, took place immediately before the dip,

Figure 9. Cross-correlation function of (left) X-ray/UVW2 and (right) UVW2/U variations over time spans (top) MJD = 57583-57724 and (bottom) MJD 57724-57840. Negative lags correspond to the first waveband listed leading the variations.

compromising our ability to determine the start time of the X-ray dip. Compared with the UVW2 flux, the UVM2 and UVW1 fluxes reached their minima later, while the U-band dip was delayed by 4 days and its recovery was completed 1–2 days later. The light curves at different wavelengths therefore possess a similar overall pattern, as well as cross-wavelength discrepancies, indicative of overlapping—but not identical—emission regions. While the earlier initial drop in UV relative to X-ray flux agrees with the Lohfink et al. (2013) picture, as does the later minimum at longer wavelengths, the recovery does not occur earlier at longer wavelengths, contradicting the model.

A superluminal knot (*K2*; see Figures 5 and 6) passed through the core in the 43 GHz VLBA images about 75 days after the start of dip 1. This conforms with the range of time delays reported by Chatterjee et al. (2009), who found a mean

delay of 68 ± 14 days. At the apparent speed of *K2*, $2.0 \text{ mas yr}^{-1} = 4.3c$, the knot traveled about 1.3 pc before reaching the centroid of the core if the angle between the velocity vector and line of sight is $\theta \sim 10^\circ$. A shorter distance to the core was derived in Chatterjee et al. (2009), based on a wider viewing angle.

In contrast with dip 1, dip 2 (see Figure 3) started with a decline in the X-ray flux, which reached its lowest level (34% below the pre-dip flux) 4.4 days before the UVW2 minimum (23% drop). As opposed to dip 1, the X-ray recovery led that at UV-optical wavelengths, although the immediate transition from the dip to a flare complicates the interpretation if the flare occurred through another process at another location. The early X-ray start implies that the dip was initiated by changes in the corona rather than the AD. This conclusion is compatible

Figure 10. UV-optical spectrum during quiescence (MJD 57655, top panel), the peak of the double flare at MJD 57783 (middle panel), and the difference between the two (bottom panel). The black dashed lines correspond to the best-fit single power laws, with spectral indices of $\alpha = 0.71 \pm 0.05$, 0.46 ± 0.03 , and -0.28 ± 0.07 for the top, middle, and bottom panels, respectively, where the flux density $F_\nu \propto \nu^{-\alpha}$. The red dotted line indicates the spectrum of a model synchrotron component with $\alpha = 1.2$. The red dashed line corresponds to the computed spectrum of a standard thin accretion disk (AD) model with inner radius $r_{\text{in}} = 1.3 \times 10^{13}$ cm and outer radius $r_{\text{out}} = 1.3 \times 10^{16}$ cm, with a temperature $T(r) = T_{\text{in}} r^{-3/4}$. (An identical spectrum would result from synchrotron emission from a nearly monoenergetic population of electrons with energies exceeding ~ 10 GeV.) In the top panel, $T_{\text{in}} = 3.0 \times 10^5$ K, while in the middle panel, $T_{\text{in}} = 4.0 \times 10^5$ K. The solid red curve shows the sum of the synchrotron plus AD models. The photometry shown in this figure is available as data (see Figure 1).

with the Chatterjee et al. (2009) scenario (see Section 1). However, the UV-optical dips and recoveries were simultaneous to within the uncertainties. This, alongside the >4 day time lag between the X-ray and UVW2 dips, is difficult to understand if the change in physical conditions in the AD propagates at a speed $\ll c$.

As was the case for dip 2, dip 3 began with a decrease in X-ray flux. However, our observational campaign ended before the flux recovered completely. Hence, we cannot perform a meaningful analysis of the behavior of the emission over the entire event.

Figure 11. Spectral energy distribution at the peak of one of the flares; no soft X-ray excess is apparent.

A pair of new superluminal knots appeared after both dips 2 (*K3* and *K4*) and 3 (*K5* and *K6*). It is possible that these knots are examples of shock pairs, with both a forward (*K3* and *K5*) and reverse (*K4* and *K6*) shock. Casadio et al. (2015) have interpreted a previously observed, closely spaced pair of superluminal knots in 3C 120 in this manner. Such a shock pair can arise from a disturbance caused by an increase in the flow velocity, as expected in the proposal of Chatterjee et al. (2009). This scenario predicts that the first knot should be faster than the second for each pair, as is the case (see Figure 6). However, the delay between the starts of dips 2 and 3 and the passage of leading knots *K3* and *K5* through the core was considerably shorter than for dip 1 and knot *K2*: 32 ± 6 days and 20 ± 6 days, respectively. This is compatible with higher actual speeds in these knots compared with *K2* only if the angle θ between the velocity vector and line of sight is much less than for *K2*, given that the apparent speed of *K2*, 4.3c, is greater than that of *K3*, 3.4c. For example, an increase in the bulk Lorentz factor Γ from 4.5 for *K2* to 5.3 for *K3* while θ decreased from 11° to 4° would correspond to the observed decrease in the apparent speed and reduce the apparent transit time to the core by 50%. This would cause an increase in the Doppler beaming factor from ~ 5 to ~ 9 , leading to knots *K3* and *K4* having much higher fluxes than their predecessors. The high-amplitude radio flare apparent in Figure 4 is consistent with this scenario: Figure 7 demonstrates that the flare is the result of knots *K3* and *K4* appearing in the jet at 43 GHz with fluxes that are extraordinarily high for superluminal knots in 3C 120. This proposed change in θ is quite large and would need to occur over a short time span. On the other hand, such a possibility might be indicated by the discrepant values from $\theta = 20^\circ$ to 3.6° derived from previous VLBA observations (Jorstad et al. 2005; Casadio et al. 2015; Jorstad et al. 2017). The proposed change in actual velocity of the flow corresponds to a relative velocity of $0.17c$, 0.29 times the sound speed of an ultra-relativistic plasma. This is consistent with the formation of a shock if the plasma contains enough non-relativistic protons to reduce its sound speed to $< 0.29c$.

Under the magnetic jet launching scenario, all X-ray/UV-optical dips could arise from occasional, probably randomly occurring, alignment of the magnetic field along the polar direction in the AD and corona (Livio et al. 2003). According to these authors, this would disable the magneto-rotational instability, disrupting the accretion flow while promoting faster flow in the polar direction into the corona and jet. In dip 1, the earlier UV flux decline suggests that the

alignment occurred first in the inner AD and then propagated (presumably at the magnetosonic speed) into the corona. In dip 2, the data imply that the alignment occurred first in the innermost AD and corona and propagated outward through the AD.

Random fluctuations in local conditions (e.g., density or temperature of the Compton scattering electrons in a section of the corona), superposed on the systematic trends (such as a short-term X-ray and UVM2 flare observed prior to dip 1), could cause enough complexity in the light curves to lead us to infer an incorrect start and end time of dips. Future observations of more such events would provide better statistics on the time delays across wavelengths.

4.3. Timescales of Variations and Cross-wavelength Lags

The time lags predicted by the AD model proposed in Section 4.1 are all <1 day, because the inner radius is only 0.12 light-hours and the radius where the blackbody spectrum peaks in the V band is only 100 times larger, 0.5 light-days. (For an area filling factor f , this size should be multiplied by $f^{-1/2}$.) This is consistent with the UV/optical lags over the period MJD 57550–57724 reported in Section 3.3 and seen in the top panels of Figure 9, although there is some longer lag present in the U band that we address below. However, longer lags are present from MJD 57726 to 57850 when slower, higher-amplitude variations occurred. This included the flare that peaked near MJD 57783. It therefore appears that the shorter-term variations are essentially simultaneous at the different wavelengths to within the limits of our sampling, while longer-term flares tend to lag at longer wavelengths by up to ~ 10 days. We present evidence in Section 4.4 that these flares occur in the parsec-scale jet rather than the AD.

Recent well-sampled, long-term *Swift* monitoring observations of the Seyfert galaxies NGC 5548 (McHardy et al. 2014; Edelson et al. 2015), NGC 4151 (Edelson et al. 2017), and NGC 4593 (Cackett et al. 2018; McHardy et al. 2018) have measured time lags between hard and soft X-ray (in some cases), UV, and optical variations, with longer-wavelength variations delayed. The ratios of the delays follow those expected from standard thin AD models (Shakura & Sunyaev 1973), but the lags at individual frequencies are a few times longer than the model would predict. The mass of the black hole in 3C 120 is within 30% of those in NGC5548 and NGC4151, (although ~ 7 times that in NGC4593 (Bentz & Katz 2015; Edelson et al. 2017)), hence one might expect similar temporal behavior. It is therefore interesting that the correlations over MJD 57550–57724 are consistent with the <0.5 day time lags predicted by the AD model, in contrast with the case of the Seyfert galaxies. There is one exception, however: the U-band variations lag those in the UVW2 band. Cackett et al. (2018) and McHardy et al. (2018) propose that the time lags longer than predicted by the AD model are caused by scattering of AD photons by emission-line clouds that lie $\gtrsim 1$ light-day from the black hole. In this scenario, supported by monitoring of emission-line fluxes, the U-band lag is longer because more distant clouds re-emit the absorbed AD radiation as Balmer continuum photons whose wavelengths fall within this band.

A qualitative similarity between *Swift* observations of 3C 120 and the Seyfert galaxies is the smoothness of the UV-optical variations of the latter compared with the X-ray fluctuations (McHardy et al. 2014; Edelson et al. 2015, 2017). Smoother UV-optical than X-ray variations in 3C 120 are

evident when comparing Figures 1 and 2. The smoothing time needed to match the X-ray with the UV timescales, ~ 4 days, is less than the mean X-ray/UVW2 lag of 6 days (see Section 3.3 and Figure 8). The smoothing time is, however, much longer than the light-travel time in the UV-optical region in the AD model. We detect no time delay in the radio galaxy between the hard and soft X-ray variations, as seen in NGC 4151 (Edelson et al. 2017). Furthermore, the spectral fits to the XRT data of 3C 120 at all epochs are consistent with a single power law (see Section 2.1 and Figure 1), with no prominent soft X-ray excess in 3C 120 in 2016–17. We note that such an excess has been reported at earlier epochs; Lohfink et al. (2013) suggested that it could be a synchrotron component from the jet. If so, the value of the maximum relativistic electron energy and/or magnetic field would need to be lower in 2016–17 in order for us not to detect a soft X-ray excess.

In the cases of NGC 5548 and NGC 4151, Gardner & Done (2017) and Edelson et al. (2017) have proposed that the lags correspond to reprocessing of coronal X-ray emission into extreme UV (EUV) photons by a hot plasma torus in the innermost portion of the accretion flow, plus the reaction time of the AD atmosphere to adjust to changes in the EUV flux. The plasma torus emits the soft X-ray excess and mediates the reprocessing of the corona’s X-rays, with the re-emitted photons heating the disk at larger radii. The double reprocessing leads to longer time delays between X-ray and UV-optical variations than predicted by the standard AD model. The lack of such a hot torus in 3C 120 in 2016–17, inferred from the absence of a soft X-ray excess, requires another explanation for the X-ray/UV time lag during dip 2 and the MJD 57726–57850 flaring episodes, and the smoothness of the UV-optical relative to the X-ray variations.

A departure of the data from the expectations of the variable AD model for the flares in 3C 120 proposed in Section 4.1 is the X-ray/UVW2 lag of -10 ± 3 days during the flaring period (see Figure 9, bottom left panel). Inspection of the light curves (Figure 2) reveals that this is mainly due to the variability over ~ 50 days following flux dip 2. Such long lags could have been caused by a disturbance starting in the innermost AD and corona that then propagated outward through the AD at a speed much less than c , heating the surface of the AD as it passed through. Such slow (as well as much slower) disturbances were inferred to propagate both inward and outward in the study of Chatterjee et al. (2009) based on correlations between X-ray and optical variability. Dip 1 could have been caused by such a disturbance that started in the AD at a radius somewhat greater than r_{in} , affecting the UVW2 and UVM2 flux first, then the corona and larger radii in the AD. However, dip 2 (Figure 3, right) started first with the X-ray decline, followed several days later by roughly simultaneous drops, and then recoveries, at all UV-optical bands. Instead, we conclude in Section 4.4 below that the X-ray and UV-optical flares following dip 2 occurred in the parsec-scale jet.

The shorter-term, relatively low-amplitude X-ray and UV-optical variations seen in 3C 120, with time lags <1 day, can potentially still be explained by heating of the disk by irradiation from a variable flux of X-rays generated in the corona (Fabian et al. 2015, 2017). The changes in X-ray flux would need to heat and cool the disk on timescales on the order of, or shorter than, the light-travel time from the corona to the affected area of the disk.

Figure 12. Sketch of model (not drawn to scale) for 3C 120 discussed in the text. The infalling clouds, whose ionized sides face the AD, scatter radiation from the corona (drawn at the base of the jet) and disk. The area filling factor of the accretion disk needs to be $\lesssim 0.5$ for most of the scattered photons to cross the disk plane toward the observer without being absorbed.

The complex longer-term, higher-amplitude variations, with time delays that extended up to 14 days in 2016–17 and temperature variations in excess of that predicted by Equation (1)—including dip 2 with its long X-ray/UV lag but no significant UVW2/V lag—requires one or more additional physical processes that contribute to the observed UV-optical flux. Propagating changes in the magnetic field, discussed in Section 4.2, might be one such mechanism. Another possible effect can be found within the “bird’s nest” geometry of thermal gas in an active nucleus (Mannucci et al. 1992; Gaskell & Goosmann 2013; Abolmasov 2017). In this picture, illustrated in Figure 12, the disk flares out into a very broad (polar opening angle $\lesssim 40^\circ$), clumpy distribution of clouds. The clouds closest to the symmetry axis (which would presumably be the jet direction in 3C 120) are essentially falling toward the black hole. If the clouds are optically thick, then they scatter into our direction light from the AD only on the side facing the disk, hence we observe scattered photons mainly from clouds on the far side of the system. This presumes that the area filling factor of the AD $f \lesssim 0.5$, such that most photons can cross the AD from the far side to reach the observer. A flare in the corona or inner disk is then both observed directly and scattered with a time delay equal to twice the distance from the inner disk to the scattering cloud. Some of the scattering might be in the Rayleigh regime, leading to wavelength dependence of the amplitude and time delays of the flux variations, as in dip 1. Thomson scattering would produce similar light-curve profiles, as in the UVM2 to V variations of dip 2, which all decreased by $12 \pm 1\%$ and varied with little or no cross-frequency lag. In such a remote scattering geometry, the short-term fluctuations would all be smoothed out, so such fluctuations are from emission viewed directly from the AD. Only major, longer-term variations would be apparent in the scattered light. Clouds located ~ 3 light-days from the inner AD have a freefall velocity of $\sim 0.05c$ and cross the region over a time of ~ 60 days. This is similar to the timescales of the flares seen in the light curves (Figure 2), although we find below that the location of the flares is in the parsec-scale jet. In order to

scatter (with an albedo a) enough radiation to cause a flux increase by a factor $(1 + x)$, a disk-shaped cloud at a radial distance r would need to have a radius $R \sim (4x/a)^{1/4} (R_{\text{AD}} r)^{1/2}$, which results in $R \sim 7 \times 10^{14} \text{ cm} = 0.3$ light-days for $x \sim 0.3$, $a \sim 0.2$, $R_{\text{AD}} \sim 2R_{\text{in}} \sim 2.6 \times 10^{13} \text{ cm}$ (the radial position in the AD where the photons that are scattered originate), and $r \sim 3$ light-days. The size requirement is therefore not excessive for such a scattering event. Furthermore, multiple clouds may be involved at any given time.

4.4. Correlation of 37 GHz and Optical-UV light Curves: Flares in the Jet

A similarity between the 37 GHz and UV-optical light curves, with a radio lag, is apparent in Figure 4. The correlation between the UVW2 and 37 GHz variations over the period of our *Swift* monitoring (Figure 13) is strong and highly statistically significant, although rather flat at lags from 10 to 40 days, indicating a mean delay of 25 days relative to UVW2. (The V/37 GHz correlation is very similar.) As seen in Figure 9, the mean X-ray/UVW2 lag during the flaring period was 10 days, for a total X-ray to 37 GHz lag of 35 days. Our sequence of VLBA images demonstrates that the 37 GHz flare in 2017 occurred mainly in knots K3 and K4 (see Figure 7). (Images available on the Boston University website⁵ show that a bright knot ejected earlier was responsible for the radio flare in early 2016, which was also preceded by an optical flare; see Figure 4.) Analysis of the sequence of VLBA images (Figure 6) indicates that K4 was crossing quasi-stationary feature A1 0.14 mas downstream of the core during the peak flux density of the 37 GHz flare. Given its apparent speed of $1.44 \pm 0.13 \text{ mas yr}^{-1}$, K4 traversed $0.14 \pm 0.1 \text{ mas}$ over 35 days, and therefore was crossing the core at the time of the X-ray flare, 0.5–1.3 pc from the black hole (see Section 4.2 above).

Because there is no plausible source of thermal radiation at 0.5–1.3 pc with the observed inverted spectral slope of ~ 0.3 of

⁵ http://www.bu.edu/blazars/VLBA_GLAST/3c120.html

Figure 13. Cross-correlation function of UVW2 and 37 GHz variations. Dotted lines have same meaning as in Figure 8. Negative lags correspond to the first waveband listed leading the variations.

the flare, we conclude that the UV-optical flare was synchrotron radiation from a narrow energy distribution of electrons, as discussed in Section 4.1 above. The most likely X-ray emission mechanism is inverse Compton scattering. The seed photons for the scattering are probably from emission-line clouds or hot nuclear dust, because the synchrotron self-Compton process would require the synchrotron flare to peak prior to the X-ray flare, contrary to the ~ -10 day X-ray/UVW2 lag. The decline in available seed photons with distance from the black hole can explain why the X-ray variations lead those at longer wavelengths.

We note that the optical light curve in Chatterjee et al. (2009) contained three major flares. Only one of these was temporally associated with an outburst at 37 GHz, with a ~ 1 month delay relative to the optical event. From this, we conclude that some, but not all, major optical flares occur in the parsec-scale jet.

Although our optical linear polarization observations (see Figure 4) are sparse, some of the measurements were obtained near the peak of the UV-optical flares. The degree of polarization P was between 1.0% and 2.2%, with the highest value occurring when χ was nearly parallel to the inner jet direction. This is consistent with turbulent plasma crossing a standing conical shock, as has been proposed to explain quasi-stationary features in relativistic jets, such as the core and A1 (Marscher 2014). Jorstad et al. (2007) reported a lower value of $P \sim 0.3\%$ at R-band in 1999–2001, which was consistent with interstellar rather than intrinsic polarization. The degree of polarization via electron scattering of thermal AD emission is expected to be considerably lower than 1% at optical wavelengths for a disk whose pole subtends an angle $\lesssim 20^\circ$ to the line of sight (Laor et al. 1990; Marin et al. 2015). The electric vector should be transverse to the polar direction, and therefore perpendicular to the jet axis. The values of P and χ that we measured during the flare are therefore inconsistent with that expected from the AD. The low degree of polarization corresponds to a rather disordered magnetic field, as is commonly found in the 43 GHz cores of compact extragalactic

jets (Jorstad et al. 2007). This conclusion is supported by the time variability of both the degree and position angle of the polarization, which is a sign of turbulence (e.g., Marscher 2014). The position angles of polarization of the moving knots appear unrelated to those measured in the R band (cf. Figures 4 and 5), hence there is no indication that they produce substantial optical emission when they are not interacting with either the core or feature A1.

Based on 15 GHz VLBA images, Leon-Tavares et al. (2010) found a coincidence between epochs of optical flares in 3C 120 and times when a superluminal knot was crossing a stationary emission feature ~ 0.7 mas from the core. Our model fits to the 43 GHz VLBA data do not include a stationary feature near the same location, although it could be confused with emission from the superluminal knots, which were ejected more frequently than normal in 2016–17. At the peak of the optical flare, there is a local maximum in the 43 GHz intensity 0.8 mas from the core. However, the feature is very weak (~ 0.07 Jy), so we consider it unlikely to be the source of the steadier UV-optical synchrotron emission inferred in Section 4.1 to be present in 3C 120 in 2016–17.

5. Summary

Our monitoring of the radio galaxy 3C 120 at X-ray, UV-optical, and millimeter wavelengths over a nine-month time span has revealed that dips in X-ray flux prior to the appearance of new superluminal radio knots are accompanied by dips in the UV-optical flux as well. Short-term, low-amplitude variations in flux in 3C 120 are well-correlated across wavelengths, with zero lag to within the uncertainties. An exception is the U band, whose variations lag by ~ 1 day, probably from scattering via Balmer continuum emission in clouds ~ 1 light-day from the black hole. In contrast, longer-term, more pronounced variations have lags from days to weeks.

The relative timing of the decline in X-ray and UVW2 flux favors an origin in the innermost AD for dip 1 and in the X-ray emitting corona for dip 2. After the minimum flux occurs in dip 1, the time for restoration of the flux to pre-dip levels is shorter in the UVW1 and UVM2 bands than at the U band, contrary to the Lohfink et al. (2013) scenario in which the inner AD is refilled from larger to smaller radii. During dip 2, the X-ray flux declines and recovers first, with the UV-optical flux varying simultaneously within the uncertainties. The time delays of the high-amplitude variations are generally longer than predicted by a standard AD model. A scenario that explains such events as the result of realignment of the magnetic field to expedite flow into the base of the jet, which plays the role of a corona of hot electrons (Livio et al. 2003; Chatterjee et al. 2009), is more consistent with the observations. An additional feature, such as the addition of scattering clouds falling toward the black hole, is needed to explain the lack of long time delays at longer wavelengths during dip 2.

A two-component model consisting of an inverted-spectrum (IS) source plus a synchrotron source with a spectral index of 1.2 can explain the UV-optical spectrum in both quiescent and flaring states. The spectral index $\alpha \sim 1/3$ of the IS source is consistent with either thermal emission from a standard thin AD or synchrotron radiation from a nearly monoenergetic population of electrons of energy ~ 10 GeV. The low-but-significant R-band polarization supports the synchrotron model and implies that the magnetic field is highly disordered in the emission region.

In contrast to observations of the radio-weak Seyfert galaxy NGC 4151 (Edelson et al. 2017), 3C 120 does not exhibit a soft X-ray excess whose variations are time-delayed relative to harder X-rays in 2016–17. There is also no evidence in the radio galaxy for a hot torus that mediates reprocessing of X-rays from the corona to heat more extended regions of the AD (Gardner & Done 2017). Instead, we find that the X-ray and UV-optical variations that we have observed in 3C 120 can be attributed to physical changes (e.g., magnetic reconfigurations) that propagate at subluminal speeds through the inner AD and corona, effects that a varying flux of X-rays from the corona have on the inner AD, and scattering of AD emission by hot clouds falling toward the AD at a distance of a few light-days from the black hole. Some longer-term flares, such as those observed in 2015–17, correspond to nonthermal radiation emitted as a superluminal knot crosses the 43 GHz core and quasi-stationary feature A1 that lies 0.14 mas from the core. As the knot crosses the core, a nearly monoenergetic population of electrons with energies above 10 GeV is added to the power-law distribution at lower energies. This could result from either magnetic reconnections (Petrovoulou et al. 2016) or diffusive shock acceleration in locations where the turbulent magnetic field has an orientation that is favorable for particle acceleration (Marscher 2014). A similar narrow energy distribution of electrons at energies $\gtrsim 10$ GeV is required by models for TeV γ -ray emission from some BL Lacertae objects (e.g., Balokovic et al. 2016).

Our observations of 3C 120 and those of Seyfert galaxies without strong relativistic jets reveal AGN to contain extremely complex environments. It appears that nearly all physical processes that can happen do occur at different times and even different locations. The emission that we observe includes photons that arrive to us (and to scattering regions) both directly and indirectly. Except for the nonthermal flares that can erupt on occasion in the parsec-scale jet, there is no obvious major difference in the observed X-ray, UV, and optical properties of 3C 120 and Seyfert galaxies as a class. Instead, the physical conditions of the inner AD and its surroundings appear rather similar. This implies that the difference between AGNs with and without powerful jets lies in the properties of the black holes and their immediate environs, such as the magnetic flux accumulated near the event horizon (Tchekhovskoy et al. 2011).

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Facilities: *Swift*, VLBA.

Software: XSPEC (Arnaud 1996), Difmap (Shepherd 1997), AIPS (van Moorsel et al. 1996), HEASoft (v6.19, 6.21; Arnaud 1996).

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