FRAMEx. II. Simultaneous X-Ray and Radio Variability in Active Galactic Nuclei—The Case of NGC 2992

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Abstract

Using simultaneous Very Long Baseline Array and Neil Gehrels Swift Observatory X-ray Telescope observations of the active galactic nucleus (AGN) in NGC 2992 over a six-month observing campaign, we observed a large drop in core 5 cm radio luminosity, by a factor of >3, in tandem with a factor of >5 increase in 2–10 keV X-ray luminosity. While NGC 2992 has long been an important object for studies of X-ray variability, our study is the first simultaneous X-ray and radio variability campaign for this object. We observe that the X-ray spectral index does not change over the course of the flare, consistent with a change in the bulk amount of Comptonizing plasma, potentially due to a magnetic reconnection event in the accretion disk. The drop in apparent radio luminosity can be explained by a change in free–free absorption, which we calculate to correspond to an ionized region with a physical extent and electron density consistent with the broad-line region (BLR). Our results are consistent with magnetic reconnection events in the dynamic accretion disk creating outbursts of ionizing material, increasing Compton up-scattering of UV accretion disk photons and feeding material into the BLR. These findings present an important physical picture for the dynamical relationship between X-ray and radio emission in AGNs.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Low-luminosity active galactic nuclei (2033); Radio cores (1341); X-ray active galactic nuclei (2035); Radio active galactic nuclei (2134); Very long baseline interferometry (1769)

1. Introduction

Over the past two decades, a deep relationship between supermassive black holes (SMBHs) and their host galaxies has been gradually revealed. The discovery that the masses of SMBHs correlate tightly with the velocity dispersion of stars in the bulge of their host galaxy (Ferrarese & Merritt 2000; Gebhardt et al. 2000) was unexpected, as the gravitational sphere of influence of an SMBH, \( r_g = GM_{BH} \sigma^2 \), is over two orders of magnitude too small to directly affect the dynamics of the stellar bulge. Consequently, a coevolution between SMBHs and their host galaxies over cosmic time must occur, in which the buildup of SMBHs and (at least) classical bulges are highly correlated processes (Kormendy & Ho 2013). One of the possible mechanisms behind this coevolution is “feedback” between the host bulge and SMBH, in which periods of SMBH accretion, when the SMBH radiates as an active galactic nucleus (AGN), affect the star formation efficiency of the surrounding interstellar medium. These processes invoke dynamic, causally connected physical structures ranging from scales of ~one hundredth of a parsec out to several kiloparsecs, each emitting in some particular range of wavelengths, giving AGNs the broadest spectral energy distributions of any astrophysical object, effectively covering the entire electromagnetic spectrum.

In 2020, we introduced the Fundamental Reference AGN Monitoring Experiment (FRAMEx; Dorland et al. 2020), an ongoing project led by the U.S. Naval Observatory to better understand the physical processes in AGNs that affect their multiwavelength apparent positions and morphologies, such as the relationship between the accretion disk and X-ray corona, and the relationship between the X-ray corona and the production of jets and other sources of radio emission. In an initial Very Long Baseline Array (VLBA) and Neil Gehrels Swift Observatory X-ray Telescope (XRT; Burrows et al. 2005) snapshot campaign of 25 AGNs that form a volume-complete sample out to 40 Mpc, we showed that the “fundamental plane” of black hole activity (e.g., Merloni et al. 2003) breaks down at high physical resolution, suggesting that core X-ray emission is (counterintuitively) better correlated with extended radio emission and raising the prospect of truly radio silent AGNs (Fischer et al. 2021).

We have since followed up with a six-month monitoring campaign, in which we observed several of the AGNs detected with the VLBA on a monthly basis with simultaneous VLBA and XRT observations, in order to explore the relationship between the X-ray and radio emission at high physical resolution in the time domain. In this work, we report on our analysis of these data for NGC 2992, an Sa galaxy (De Vaucouleurs et al. 1991) in the early stages of a merger with its neighbor NGC 2993 (e.g., Duc et al. 2000). Previous work on NGC 2992 demonstrated the presence of an extended, “Figure 8” loop of radio emission (Ulvestad & Wilson 1984; Weller & Morris 1988) symmetric about the galactic nucleus, likely a product of conical outflows (e.g., Marquez et al. 1998; Chapman et al. 2000; Veilleux et al. 2001) driven by the AGN (Friedrich et al. 2010), which is the dominant ionization source in the inner kiloparsec (e.g., Guolo-Pereira et al. 2021).
NGC 2992 is particularly variable in the X-rays, exhibiting 2–10 keV luminosity changes of over an order of magnitude (e.g., Gilli et al. 2000), sometimes within days-to-weeks time frames (Murphy et al. 2007). This extreme variability has been implicated in the spectral changes that NGC 2992 exhibits at visual wavelengths, varying between a Seyfert 1.5 and a Seyfert 2 without measurable changes in line-of-sight reddening (Trippe et al. 2008), tying the 2–10 keV emission to ionizing continuum variability. At hard X-ray energies (>10 keV), NGC 2992 presents a simple power-law spectrum that exhibits variability similarly to the soft X-ray emission (Beckmann et al. 2007). When considered jointly with the soft X-ray emission, both the power-law spectral index $\Gamma$ and the hydrogen column density $N_H$ are relatively constant over time, leading Beckmann et al. (2007) to argue that the X-ray luminosity variability in NGC 2992 could be due to varying amounts of coronal plasma, as might be provided by flares attributed to magnetic reconnection events in the SMBH accretion disk.

X-ray emission line spectroscopy has shed light on the nature of the X-ray flares in NGC 2992, with Murphy et al. (2007) noting that a highly redshifted, broad Fe Kα line appears during periods of high X-ray luminosity, as later confirmed by Shu et al. (2010), in contrast to Fe Kα emission at 6.4 keV normally found in the X-ray spectrum and attributed to more distant matter, as noted also in Yaqoob et al. (2007b). Other K-shell emission lines of Si and S near their rest-frame energies were later detected using higher spectral resolution observations during a period of lower X-ray luminosity, but these observations also demonstrated the existence of Si lines redshifted by 2500 km s$^{-1}$, indicating powerful AGN-driven outflows in NGC 2992 (Murphy et al. 2017). In X-ray absorption, Marinucci et al. (2018) recently found tentative evidence for an “ultra fast outflow,” with material being ejected from the innermost accretion regions with a velocity of about 0.21c, and a triggered simultaneous broadband campaign by Marinucci et al. (2020) also showed a transient emission line at 5.4 keV, which the authors attributed to a component just a few gravitational radii away from the black hole in the highly variable accretion disk.

The overall picture of NGC 2992 then is one of a powerful AGN, possibly triggered by the merger with NGC 2993, that is driving material out of the center of the galaxy to large physical scales. The AGN is highly variable, with several distinct kinematic components and changes in spectral type (between type 1 and type 2) over short timescales, providing a direct probe into the innermost accretion processes of AGNs. The AGN in NGC 2992 is therefore an excellent case study for models of AGN accretion, as was noted by Yaqoob et al. (2007a) and Murphy et al. (2007).

Despite the rich multiwavelength variability demonstrated in this AGN, to date no study of the radio variability in NGC 2992 has been conducted. This is a major deficiency, as while the X-ray emission in AGNs is a proxy for the thermal accretion luminosity (via inverse Compton scattering of disk UV photons), the radio emission traces the nonthermal, magneto-hydrodynamic interaction of BH/accretion disk magnetic fields and high-energy electrons responsible for putative jet activity (for a review, see Blandford et al. 2019). Moreover, while there have been entire very long baseline interferometry (VLBI) monitoring campaigns of luminous AGN jets (e.g., Lister et al. 2009, 2016), there have been only a handful of VLBI monitoring campaigns of nearby radio-quiet AGNs (e.g., Blundell et al. 2003; Wang et al. 2021), and to our knowledge none with simultaneous X-ray and radio monitoring.

In this paper, we discuss the results of a time-domain campaign to study the simultaneous VLBA C-band (5 cm) core radio and Swift XRT 0.2–10 keV X-ray properties of the AGN in NGC 2992. The main goal of this paper is to explore the temporal relationship between radio core and X-ray emission in AGNs, and what this relationship reveals about the accretion process in AGNs. In Section 2, we describe our observation campaign and the VLBA and Swift XRT data analysis. We present our results in Section 3, provide discussion in Section 4, and give our main conclusions in Section 5.

2. Methodology

We use a redshift $z = 0.00771$ (Keel 1996) and a distance $D = 33.2$ Mpc for NGC 2992, as in Fischer et al. (2021), giving an angular scale of 0.16 pc mas$^{-1}$. For the black hole mass, we use the calcium triplet based measurement of $\sigma_v = 154$ km s$^{-1}$ from Caglar et al. (2020) and the $M_{BH} - \sigma_v$ relation from Korndey & Ho (2013), which gives a logarithmic $M_{BH} \sim 8.00$, with an intrinsic scatter-based uncertainty of 0.28 dex.$^5$ The corresponding Eddington luminosity is $1.3 \times 10^{46}$ erg s$^{-1}$. The bolometric luminosity of the AGN in NGC 2992 was estimated at $8.3 \times 10^{46}$ erg s$^{-1}$ by Woo & Urry (2002), who compiled a catalog of black hole masses and bolometric luminosities for AGNs. A comparison with similarly derived bolometric luminosities from Padovani & Rafanelli (1988) indicates a dispersion of $\sim 0.33$ dex (Figure 5 in Woo & Urry 2002), and the value from Woo & Urry (2002) is consistent with that derived in García-Bernet et al. (2015). The Eddington ratio of the SMBH in NGC 2992 is therefore $L_{bol}/L_{Edd} \sim 0.0064$, with an uncertainty of about 0.44 dex.

2.1. Very Long Baseline Array Observations

We received observation time through the U.S. Naval Observatory’s 50% timeshare (P.I. T. Fischer) allocation on the VLBA telescope at 5 cm (6 GHz) every 28 days starting 2019 December 31 to perform a total of six observations at regular intervals. Utilizing the phase referencing method from the initial FRAMEx snapshot survey (Fischer et al. 2021), we altered telescope pointings between our target and a nearby known phase reference calibrator. In this way, we are able to accurately constrain the position and phase of NGC 2992. We move between our target and the phase calibrator after 4 and 2 minutes integration times, respectively. We observed NGC 2992, along with two other targets of similar R.A. from our FRAMEx series, which are also observed using the phase referencing technique. We cycled between the three targets in 20 minutes on-source time intervals in order to maximize uv coverage so that we can produce high fidelity images for each source. We observed NGC 2992 for a total integration time of 1 hr and requested to use all 10 VLBA antennas in each observing session. Unfortunately, the two observing sessions on 2019 December 31 and 2020 April 21 did not use all 10 antennas; 2019 December 31 did not use HV and OV and 2020 April 21 did not use MK. The results of the other two FRAMEx targets observed along with NGC 2992 will be presented in a future work.

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$^5$ We note that this black hole mass is 2.2 times lower than the value adopted in Fischer et al. (2021).
We used the new, shared-risk, Mark 6 data recorders, which provide 4 Gbps recording rate and enable dual polarization observations over 512 MHz of continuous bandwidth. We used 2 bit sampling and four, 128 MHz, intermediate frequency (IF) windows each with 512 channels for a spectral resolution of 250 kHz. Due to the shared-risk nature of the Mark 6 data recorders, during our 2020 February and March set of observations, there was an unforeseen software bug in the NRAO’s configuration of the recorders, which affected our 6 GHz setup (Section 2.1.3). The results of this software bug are that we lost the fourth IF window for observations during these two months and there was a residual amplitude scaling issue that affected our flux measurements. We carefully addressed these issues in Section 2.1.3. Table 1 presents our observation parameters for the six sessions in which we observed NGC 2992.

### 2.1.1. Calibration

To calibrate the VLBA data obtained from our observations, we used NRAO’s software package, Astronomical Image Processing System (AIPS; Greisen 2003) release 31DEC19. We first loaded in the data with a calibration (CL) table interval of 0.1 minute. Next, we used the VLBAUTIL module, which corrected for the ionospheric delays and Earth orientation parameters. Before the sample threshold errors were corrected, we used the task TYSMO to clip the system temperature (\( T_{\text{sys}} \)) table (TY) values above a factor of ~2 times the average \( T_{\text{sys}} \) values over the duration of the observation. We flagged \( T_{\text{sys}} \) values below 0 K since these are either nonphysical or from other instrumental effects. This task then replaced the clipped values by interpolating across the clipped region using a linear interpolation function. In addition to flagging spurious system temperatures, we also flagged data below 15° elevation. Next, we flagged out any high-amplitude radio frequency interference (RFI) as a function of time using the task EDITR and then flagged RFI as a function of frequency using the task WIPER.

We note that the Brewster and Kitt Peak antennas consistently had major RFI throughout all observations, which required significant flagging. Once flagging was complete, we calibrated for correlator sampler threshold errors, instrument delays, bandpass, amplitude, and parallactic angle. We checked to see if there were any bad solutions applied to the CL table using EDITR and flagged them out. Next, we solved for phase and complex amplitudes with the task FRING and applied the solutions to the CL table for both the phase calibrator and source using the task CLCAL. We checked the last calibration table using EDITR and WIPER again and flagged out any bad solutions. Finally, we applied the phase calibrator’s CL table to the source using the task SPLIT and a two-point interpolation function, thus preserving the calibrated phase and absolute astrometry to the accuracy level of the phase calibrator’s position. We used the phase calibrator J0941−1335 from the ICRF3 catalog (Charlot et al. 2020), at position \( \alpha = 145°2606228293, \delta = −13°597495756639 \). Before imaging, we flagged any remaining high amplitudes on the source and calibrator using the task WIPER.

### 2.1.2. Imaging

To image the calibrated data, we used the AIPS task IMAGR. We set the cell size to 0.8 mas and the image size to 512 × 512 pixels. This makes the field of view for each image 0″41 × 0″41. Next, we set the Briggs robustness to close to 0 to weight the data towards the source. Before imaging, we used the task JMFIT to fit the source model and use this source model to remove any residual structure in the data. Once the residual structure was removed, we applied the image solution to the source and used this to estimate the peak and integrated flux densities. We then applied the image solution to the source and used this to estimate the peak and integrated flux densities.

### 2.1.3. Radio Analysis

Using NRAO’s AIPS software, we used the task JMFIT to analyze each epoch’s final cleaned image. After setting the parameters to search inside a designated box, this task used an elliptical Gaussian fitting algorithm with the image’s rms to calculate the FWHM of the source to obtain the peak and integrated flux densities with their respective \( \sigma \) uncertainties. To account for any systematic uncertainties and for a conservative treatment of the total uncertainty in these data, we used two times the \( \sigma \) errors and denote it as \( 2\sigma \). Table 2 contains the results for the VLBA measurements.

### Table 1

| Antennas (Missing) | Date       | \( T_{\text{int}} \) (s) | \( f_{\text{center}} \) (GHz) | Bandwidth (MHz) | \( f_{\text{image}} \) (GHz) | Restoring Beam (\( \alpha \times \delta \); mas) | Beam Angle (deg) | rms (\( \mu \text{Jy beam}^{-1} \)) | rms \( \text{model} \) (\( \mu \text{Jy beam}^{-1} \)) |
|-------------------|------------|--------------------------|-------------------------------|-----------------|-----------------------------|---------------------------------------------|-----------------|-------------------------------|----------------------------------|
|                   | 2019 Dec 31| 2564                     | 5.803879                      | 384             | 5.612−5.996                 | 7.23 × 3.32                                  | −8.0            | 45                            | 29                               |
|                   | 2020 Jan 27| 3268                     | 5.805074                      | 384             | 5.612−5.996                 | 7.56 × 2.64                                  | −4.2            | 42                            | 20                               |
|                   | 2020 Feb 25| 3036                     | 5.801782                      | 384             | 5.612−5.996                 | 8.02 × 2.16                                  | −6.7            | 56                            | 21                               |
|                   | 2020 Mar 25| 2796                     | 5.796680                      | 384             | 5.612−5.996                 | 9.80 × 4.33                                  | 2.9             | 57                            | 22                               |
|                   | 2020 Apr 21| 2788                     | 5.808148                      | 384             | 5.612−5.996                 | 7.76 × 3.21                                  | −5.7            | 52                            | 24                               |
|                   | 2020 May 19| 3260                     | 5.806133                      | 384             | 5.612−5.996                 | 8.05 × 2.99                                  | −3.8            | 45                            | 20                               |

Note: Phase Calibrator J0941−1335

We used the new, shared-risk, Mark 6 data recorders, which provide 4 Gbps recording rate and enable dual polarization observations over 512 MHz of continuous bandwidth. We used 2 bit sampling and four, 128 MHz, intermediate frequency (IF) windows each with 512 channels for a spectral resolution of 250 kHz. Due to the shared-risk nature of the Mark 6 data recorders, during our 2020 February and March set of observations, there was an unforeseen software bug in the NRAO’s configuration of the recorders, which affected our 6 GHz setup (Section 2.1.3). The results of this software bug are that we lost the fourth IF window for observations during these two months and there was a residual amplitude scaling issue that affected our flux measurements. We carefully addressed these issues in Section 2.1.3. Table 1 presents our observation parameters for the six sessions in which we observed NGC 2992.
thermal noise values are systematically lower for these months across all of our targets observed in the sessions containing NGC 2992. As was previously noted in Section 2.1, a software bug impacted our observations. We used new Mark 6 data recorders under “shared-risk,” thus assuming responsibility for any systematics in the new recording system that might cause issues. Through private communications with several NRAO experts responsible for managing the VLBA, we learned that the software bug was thought to have been associated with repeated drop-outs in the data recorders. However, if the recording drop-out was the only issue, then the amplitudes for each of the calibrators and targets should have been corrected when self-calibration was applied. Unfortunately, self-calibration did not improve the amplitudes nor rms thermal noise properties in any of the phase calibrators. Thus, there were likely issues beyond those identified by NRAO. The instrumental effects went beyond coherence losses, as these would have been corrected during self-calibration and we would have recovered the expected amplitudes for each of our targets. Because our data continued to suffer from these dramatic intensity offsets during the months of February and March, we turned to an analytic approach to correct the data.

We examined the peak intensities for all objects observed during the same runs as NGC 2992. These include the following phase calibrators and respective targets: PMN J0941−1335 for NGC 2992, JVAS J0956+5753 for NGC 3079, and JVAS J1206+3941 for NGC 4151. Figure 3 shows the ratio between self-calibrated and non-self-calibrated peak intensities for the three phase calibrators. Since these ratios are consistent with one, we used the non-self-calibrated peak intensities for all sources in our analysis as we are unable to self-calibrate the observations of NGC 2992 due to its low intensity. Because the ratios in Figure 3 are consistent with ~1 across all epochs, this implies that self-calibration is inadequate to correct for the

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**Figure 1.** The 6 GHz (5 cm) images of NGC 2992. Position centered at R.A.(J2000) = 146°42476 and decl.(J2000) = −14°326274. Red contour is four times the image rms with subsequent contours at 8, 12, and 16 times image rms in blue. The restoring beam is to the lower left of each image in green. (For the observations on 2020 February 5 and March 25, these images have been corrected using the scaling factor.)
amplitude drops for the problematic sessions in the months of February and March.

The top of Figure 4 shows the peak intensities of the phase calibrators for all observations including the problematic sessions in February and March. We found that every object observed during these months exhibit a similar decrease in peak intensity. As it is unknown if both observations are affected equally, we needed to determine a scaling factor for each one. In order to ascertain whether we obtained the correct scaling factor, we devised two independent methods to estimate it.

The first method utilizes the peak intensities $I_{\nu}$ to calculate the ratio of the unaffected data to the affected data for each phase calibrator and source (excluding NGC 2992). We took the ratio of intensities for each affected observation $a$ to the unaffected ones across observations, giving a scale factor $f_{\text{peak}} = I_{\nu}/I_{\nu, \text{a}}$, where we used the inverse variances $\sigma_{I_{\nu}}^{-2}$ as weights. Using standard error propagation, the uncertainty of the scaling factor is:

$$\sigma_{f_{\text{peak}}}^2 = \left( \frac{\sigma_{I_{\nu}}}{I_{\nu, \text{a}}} \right)^2 + \left( \frac{I_{\nu} \sigma_{I_{\nu}}}{I_{\nu, \text{a}}^2} \right)^2$$

(1)

where $I_{\nu, \text{a}}$ is the peak intensity for the affected data and $\sigma_{I_{\nu}}$ is its associated uncertainty. This allowed us to obtain a total of
eight scaling factors for each object based on comparing the four unaffected observations with the two affected observations (four scaling factors for each affected epoch).

The second method examines a cleaned, non-self-calibrated image of every calibrator and source (excluding NGC 2992) to compare the rms from the noise of the unaffected with that of the affected observations. The first issue that needs to be corrected for before comparing the rms values is the fact that not all observations utilize all 10 VLBA antennas. To account for this, we took the ratio of the observed rms to the theoretical rms for each observation, calculated using the number of antennas used, integration times, and the total used bandwidth. This enabled us to have the most accurate comparison between all observations. Our final scaling factor, \( f_{\text{RMS}} \), for the rms method is derived using the following:

\[
 f_{\text{RMS}} = \left( \frac{\text{RMS}_{\text{meas}}}{\text{RMS}_{\text{theo}}} \right)^{1/2}.
\] (2)

We then found the individual scaling factors from each unaffected observation to be consistent with those of the first method in which we obtained four scaling factors for each object’s affected epoch. Since the associated uncertainties of the rms ratios are negligible, variance in the scaling factor from the rms method represents real dispersion. Figure 5 shows the uncorrected (top panel) and corrected (bottom panel) rms thermal noise values for all six epochs for each phase calibrator. Similarly, Figure 6 shows the uncorrected (top panel) and corrected (bottom panel) rms thermal noise for the other two FRAMES sources, NGC 3079 and NGC 4151, and NGC 2992.

Since the scaling factors obtained by the two methods are independent of each other, we first compared Methods 1 and 2 by plotting the individual scaling factors as shown in Figures 7 and 8. We also plotted the scaling factors for NGC 2992 based on the rms method and inferred their location in the plot, which was not included in the scaling factor analysis, based on its rms values.

There is an overall linear relationship between both methods, indicating that the scaling factor is different for each object. Since the scaling factor is multiplicative, we examined the reduced chi-squared \( \chi^2_{\text{red}} \) in log space to determine the difference between the two methods. The calculated \( \chi^2_{\text{red}} \) is 72.8 for 2020 February 25 and 60.7 for 2020 March 25,
indicating an additional uncertainty \( s \), which we calculated by solving for \( \chi^2_{\text{red}} = 1 \):

\[
1 = \frac{1}{N - 1} \sum_{i=1}^{N} \frac{\left( \text{MD}_i - \text{MD} \right)^2}{\sigma^2_{\text{MD}_i} + s^2}
\]

\[
(3)
\]

MD are the logarithmic differences between Methods 1 and 2. We found that \( s = 0.12 \) dex and 0.17 dex for 2020 February 25 and 2020 March 25, respectively. Since Method 2 uses the most data and is unaffected by any real intrinsic variability as may be seen in AGNs, we used Method 2 to estimate the scaling factor, and added in quadrature the additional uncertainty \( s \). To reiterate: both Methods 1 and 2 compare the two affected observation dates with the four unaffected observation dates, so we took as the fiducial scaling factor for each affected data the average ratio between the rms of the observation with the four values from the unaffected data. As only the formal flux uncertainties were included in the error term \( \sigma_{\text{MD}} \), the intrinsic uncertainty term \( s \) gives the dispersion on the mean per-object scaling factor.

To robustly estimate the errors on the flux densities (peak and integrated), we performed a Monte Carlo simulation for each object, with \( 10^6 \) random draws. On each draw, a random value from a log-normal distribution with sigma equal to the intrinsic dispersion was taken (the intrinsic dispersion is multiplicative and therefore calculated in log space), and converted to a linear value. To this we added a random value from a normal distribution with sigma equal to the formal flux density uncertainty. The final error was associated to the flux density and stored in a vector, from which we derived the final 95.4% confidence interval.

For NGC 2992, we took the conservative approach and used the largest scaling factor for each affected data set, 1.7 for the February data and 1.4 for the March data. Each object’s scaling factor was used to correct their respective rms and intensities of the affected observations. These corrections are included in the bottom panels of Figures 4–6, and 9. Corrections are also included in Figure 11 and Table 2.

One caveat to note: NGC 2992’s rms for the affected observations do not follow the same trend when compared to the phase calibrators and sources. The rms values are consistent throughout the 6 month survey. The only factor that appears to be different is that NGC 2992’s rms values are significantly closer to the theoretical rms values. The ratios of the rms and theoretical rms for the other sources of the affected observations are all >6, while for NGC 2992 it is ~2. To err on the side of caution, however, we applied a scaling factor to the NGC 2992 data, which has the effect of lessening the observed radio variability.
Figure 9 shows the peak fluxes that include the two other FRAMEx sources, NGC 4151 and NGC 3079, before and after applying our scaling correction to the problematic data sets. From this analysis we see that the respective scale factors when applied to the other targets in our sample do a robust job in correcting the fluxes during the trouble epochs. We note that NGC 4151 has only ~2 times the average flux of NGC 2992, implying that our nondetections during the sessions that suffered the software bug problems are, in fact, likely real. Through private communications with VLBA experts at NRAO, we employed numerous methods both in calibration and imaging to correct these troubled sessions but in the end, we found the scaling method described above most accurately and appropriately corrected our amplitudes.

2.2. Swift XRT Observation

We obtained Target of Opportunity observations (ToO; PI: N. Secrest) using the Swift XRT, which has a point-spread function (PSF) with a half-power diameter of 18" at 1.5 keV and a positional accuracy of 3". We requested an integration time of 1.8 ks using Photon Counting (PC) mode and generated the X-ray spectra using the online XRT product generator (Evans et al. 2009), setting the same coordinates as the VLBA targeting coordinates. During our requested observation time in 2020 February and April other science projects took priority. Therefore, we only have simultaneous X-ray data for four out of six VLBA observations. In Table 3 we present the Swift XRT parameters used for our observations of NGC 2992.

2.2.1. X-Ray Analysis

Spectral analysis was performed using XSPEC v.12.11.1 (Arnaud 1996) software. We checked for variability using our XRT data alongside the 8 band spectrum from the 105 month BAT catalog. This spectrum covers the period between 2004 December and 2013 August and has an effective integration time of 5.9 yr, providing a measure of the average intrinsic hard X-ray luminosity of NGC 2992. Folding in both XRT and BAT data spectra then provides the best way to see how our short-term data vary from the long-term average. We used a simple absorbed power-law model (phabs*zphabs*zpow) to fit the X-ray spectra (shown in Figure 10). There is soft excess seen in the 0.5–2 keV range as well as the possible appearance of Fe Kα and Kβ lines in some of the observations. Fitting the spectrum with the physical model MYTorus (Murphy & Yaqoob 2009) helped to account for them, but did not produce an overall better fit, likely owing to a small column density of \( N_H \sim 10^{22} \text{ cm}^{-2} \) (Fischer et al. 2021). Therefore, we continued fitting the spectrum using the absorbed power-law model and produced Monte Carlo Markov chains using the chain command to robustly estimate model errors and covariances.

Initially, we tied all parameters for the XRT data to the BAT data, but this resulted in a poor fit. We untied the power-law normalization, hydrogen column density, and photon index parameters in a number of combinations to see if there were any statistically significant differences between the free parameters. From our Markov chain analysis, we found that there is no significant evidence of variability in either the hydrogen column density \( N_H \) or the photon index \( \Gamma \) when left as free parameters (or when one parameter is tied and the other is left free to vary). Only the variations of the normalization parameters were statistically significant, indicating that while the shape of the X-ray spectrum is invariant, the overall X-ray luminosity varies. Consequently, we tied \( N_H \) and \( \Gamma \) for all data sets, and ran Markov chains to calculate the statistical uncertainty on the intrinsic 2–10 keV flux.

Table 3

| ID      | R.A.  | Decl.  | Mode (deg) | UTC Start         | UTC Stop          | Obs. Time |
|---------|-------|--------|------------|-------------------|-------------------|-----------|
| 35344   | 146°24'7756 | −14°32'6689 | PC         | 2019 Dec 31 12:54 | 2019 Dec 31 15:25 | 1692      |
| 35344   | 146°24'7756 | −14°32'6689 | PC         | 2020 Jan 28 10:13 | 2020 Jan 28 11:08 | 1682      |
| 35344   | 146°24'7756 | −14°32'6689 | PC         | 2020 Mar 25 09:38 | 2020 Mar 25 10:33 | 1687      |
| 35344   | 146°24'7756 | −14°32'6689 | PC         | 2020 May 19 02:30 | 2020 May 19 03:25 | 1707      |

3. Results

3.1. Flux Variability at 6 GHz

Examining the results from the calibrated and imaged data, NGC 2992 was marginally detected on 2020 February 25 and not detected in our observation on 2020 March 25. It appears to drop below our detection limit given our integration time of ~1 hr. Using the scaling factors (from Section 2.1.3), we calculated the 3σ upper limit to be 0.5 mJy for this observation. The peak flux density falls to less than half the average of ~1 mJy.

This type of variability has not been typically seen in radio-quiet AGNs, largely because there are almost no studies of radio variability in these types of objects and even fewer at the resolution of the VLBA (let alone simultaneous X-ray and radio studies to probe the inner workings of radio-quiet AGNs). Of those found in the literature for radio-quiet AGNs, Falcke et al. (2001) reports on two surveys: radio-quiet quasars (RQQs) observed with the Very Large Array (VLA) and low-luminosity AGNs (LLAGNs) observed with the VLA and the VLBA. For both the RQQs and LLAGNs, a large number were found to be variable over the span of a year. Mundell et al. (2009) examined Seyfert galaxies with the VLA and found flux variations over a 7 yr period. Out of 12 detected sources, 5 where found to be variable; excluding NGC 2110, which is a radio-loud AGN, the average variation is ~0.3 mJy, or ~45%. The only similar property found between them is compactness of their cores. The authors suggest that these sources might therefore exhibit variability. The remaining detected sources have associated extended emission (either jet-like or non-relativistic). Only NGC 2110 has a variable compact core and extended emission from a radio jet. Although both of these works have stated long-term radio monitoring campaigns are needed to better understand these objects, few exist in the literature.

Next, we examined the brightness temperature \( T_b \) for the peak intensity values found in Table 2. Starting with the Rayleigh–Jeans limit for brightness temperature (Condon & Ransom 2016), we converted this expression by substituting the flux density to brightness units per solid angle where the
solid angle is converted to the area of a Gaussian beam. All of the constants were combined into one term with units (including K) that cancel the remaining variables leaving only the unit K. The brightness temperature expression for radio emission is therefore expressed as

$$ T_b = 1.222 \times 10^3 \frac{L}{\nu^2 \theta_{\text{max}} \theta_{\text{min}}} $$

(4)

where $I_\nu$ is the peak intensity in mJy beam$^{-1}$, $\nu$ is in GHz, and $\theta_{\text{max}}$ and $\theta_{\text{min}}$ are the Gaussian major and minor axis half-power beam widths, in arcseconds, used to determine the peak flux. The corresponding brightness temperature is $\sim 10^6$ K, but because the source is unresolved, this is a hard lower limit.

The presence of the unresolved radio variability allows us to set better constraints on the minimum brightness temperature $T_{b\nu}$, which can yield insights into the size and nature of the emitting region. For a spherical blackbody, the Rayleigh–Jeans expression for the luminosity density is:

$$ L_\nu = \frac{2\nu^2 k_B T_b}{c^2} 4\pi r^2, $$

(5)

where $r$ is the radius of the emitting source. Given variability in $L_\nu$, with some characteristic timescale $\tau$, the size of the source is set by $r = c\tau$. Rearranging Equation (5), the brightness temperature is:

$$ T_b = \frac{L_\nu}{8\pi \nu^2 k_B \tau^2}, $$

(6)

which is equivalent to Equation (6) in Metzger et al. (2015) in the limit of $\nu/c \ll 1$ (material not expanding at a significant fraction of the speed of light, such as a jet). There could, however, be variations in the radio on shorter timescales than our observations sample, so Equation (6) provides a minimum brightness temperature of the emitting source. For a timescale of 28 days corresponding to the sampling of our observations and the minimum observed luminosity from Table 2, $T_{b,\text{min}} \sim 10^9$ K.

**Table 4. X-Ray Spectral Fitting Results for NGC 2992**

| Observation Date | Normalization ($\times 10^{-2}$) | $\log_{10}(F_{2-10\text{keV}}/\text{erg cm}^{-2}\text{ s}^{-1})$ | $\log_{10}(L_{2-10\text{keV}}/\text{erg s}^{-1})$ |
|------------------|---------------------------------|---------------------------------------------------------------|-----------------------------------------------|
| 2020 Dec 31      | 0.61$^{+0.10}_{-0.12}$         | $-10.65^{+0.04}_{-0.05}$                                     | $42.47^{+0.04}_{-0.05}$                        |
| 2020 Jan 28      | 3.34$^{+0.05}_{-0.01}$         | $-09.93^{+0.04}_{-0.04}$                                     | $43.20^{+0.04}_{-0.04}$                        |
| 2020 Mar 25      | 3.71$^{+0.06}_{-0.07}$         | $-09.87^{+0.03}_{-0.03}$                                     | $43.25^{+0.03}_{-0.03}$                        |
| 2020 May 19      | 1.84$^{+0.06}_{-0.30}$         | $-10.18^{+0.04}_{-0.04}$                                     | $42.94^{+0.04}_{-0.04}$                        |

**Note.** Using the phenomenological model $\text{phabs} \times \text{zphabs} \times \text{zpow}$ to fit the contemporaneous data, only the normalization has changes that are statistically significant. Uncertainties for the normalization and flux were calculated using Markov chains. The rest of the parameters were tied to the 105 month BAT survey, giving a total ratio of statistic over degrees of freedom of 1184.74/1421, an $N_H$ of $1.0^{+0.1}_{-0.2} \times 10^{22}$ cm$^{-2}$, and a photon index ($\Gamma$) of $1.8^{+0.1}_{-0.2}$.

$^a$ All uncertainties calculated are the 95.4% confidence interval.
K. This brightness temperature, combined with the overall low radio luminosity of the AGN, strongly favors a self-absorbed synchrotron source consistent with the hot compact hard X-ray corona.

3.2. Soft X-Ray Variability

We show the X-ray spectra of NGC 2992 in Figure 10. Using a simple power-law model, we found that there is variability consistent with what has been found previously (Murphy et al. 2007; Marinucci et al. 2020) in the 2–10 keV regime. The photon index (Γ) and column density (NH) do not vary from epoch to epoch, with NH = 1.0+0.1 −0.1 × 1022 cm−2 and Γ = 1.8+0.2 −0.1. Table 4 contains the power-law normalization variations from the fitted data with the calculated logarithmic F2–10 keV and L2–10 keV.

3.3. X-Ray and Radio Appear Anticorrelated

In Figure 11 we show the normalized flux for the contemporaneous X-ray (2–10 keV) and radio (~6 GHz) observations. There appears to be an anticorrelation such that when the X-ray flares, the radio emission is attenuated, and as the X-ray flux diminishes, the radio emission reappears. While we lost simultaneous observations in February and April, the overall anticorrelation trend is nonetheless clear.

3.4. Faint Secondary Radio Emission

Examining the image from the concatenated unaffected data (Figure 2), there appears to be evidence of a faint radio emission source to the SE of the core radio emission. It is separated by 22.3 mas from the peak intensity of the core radio emission to that of the faint source. Located at RA 146°4247702 and decl. −14°23262833, it has a significance of ≥5σ. The faint emission has a peak intensity of 0.15 ± 0.02 mJy beam−1, which corresponds to a lower limit brightness temperature T_b ~ 10⁵ K. This most closely resembles free–free emission seen similarly in NGC 1068 (Gallimore et al. 2004). It is unclear at this time if this is previously ejected material from the core of NGC 2992. Since this image is from multipod observations, a follow-up observation is needed with a longer integration time (~4 hr) to confirm the extent of the faint emission.

4. Discussion

4.1. Radio Variability

There are a few physical mechanisms that can help explain the variability seen in our observations. We begin with the most likely scenario and discuss other possibilities.

4.1.1. Free–Free Absorption

The 6 GHz core radio emission in NGC 2992 exhibited a decline by a factor of at least ~3 over a 3 month period, in tandem with a 2–10 keV flare, before recovering at the end of the flare. While the literature on the potential physical mechanisms behind simultaneous X-ray and radio variability of radio-quiet AGNs is lacking, some work on black hole binaries (BHBs) may be informative. For example, Fender et al. (1999) report a drop in radio emission, which they report as a jet, in the BHB GX 339–4 throughout a period of high X-ray luminosity. Both the MOST (36 cm) and ATCA (3, 6, and 20 cm) radio emission and the BATSE 20–100 keV flux plummet in tandem with an outburst in the 2–12 keV RXTE ASM flux (see their Figure 1). The entire event occurs over a period of 400 days, and the behavior is attributed to the innermost accretion disk extending closer to the BH, diminishing the Comptonizing corona and extinguishing emission at hard X-rays.

This “high-soft, low-hard” paradigm has been proposed to unify BHB and AGN accretion states (e.g., Küder et al. 2006); however, to date no evidence has been found for a similar anticorrelation between the hard and soft X-rays in NGC 2992, and the constancy of X-ray spectral index Γ found here and in previous studies (e.g., Murphy et al. 2007; Beckmann et al. 2007) argues strongly against this picture. Indeed, the constancy of the X-ray spectrum over a factor of ~8 variation in apparent luminosity suggests, as was argued in Beckmann et al. (2007), that the amount of Comptonizing plasma has varied, e.g., as might be caused by magnetic reconnection events in the innermost accretion disk (e.g., Poutanen & Fabian 1999; de Gouveia Dal Pino et al. 2010). In this case, a burst of Comptonizing plasma increases the bulk number of up-scattered UV photons from the accretion disk, leading to a change in X-ray luminosity without a significant variation in spectral index.

A possible explanation for the simultaneous radio variability of NGC 2992 is changes in free–free absorption. Given that the
decrease in radio emission is accompanied by an increase in the X-ray flux, this indicates higher levels of activity, which can result in ionized material being ejected from the accretion disk, either a cloud or a wind, and potentially passing between the nuclear radio source and the observer, increasing the opacity at radio frequencies and dimming the flux.

We have from Osterbrock (1989) that the optical depth due to free–free absorption can be calculated using the following expression:

$$\tau_f = 3.28 \times 10^{-7} \left( \frac{T}{10^4 \text{ K}} \right)^{-1.35} \left( \frac{\nu}{\text{GHz}} \right)^{-2.1} E$$

(7)

where $T$ is the temperature of the ionized gas in units of $10^4$ K, $\nu$ is the observed frequency in GHz, and $E$ is the emission measure, which corresponds to the following expression:

$$E = \left( \frac{\int n_e n_+ \, ds}{\text{pc cm}^{-6}} \right).$$

(8)

We can assume that $n_+ \sim n_e$, so the emission measure is the integral of $n_e^2$ along the line of sight. Based on the values from Table 2 we can calculate that, relative to the average flux of the first two and last two data points, one would need an ionized source with an optical depth $\tau_6 \text{GHz} = 0.71$ in order to reduce the 2020 Mar 25 flux to the observed 3σ upper limit of 0.5 mJy.6

Combining this optical depth value with Equation (7), we were able to calculate the electron density ($n_e$) as a function of thickness of the intervening ionized region, for temperatures $T = 10^4, 10^5,$ and $10^6$ K. We also calculated the corresponding electron column densities ($N_e$). These results are presented in Figure 12, where we can see that an intervening cloud with a thickness in the range $10^{-6} \leq l \leq 5 \times 10^{-4}$ pc and electron densities in the range $4 \times 10^5 \leq n_e \leq 2 \times 10^8$ cm$^{-3}$ will result in this optical depth. These values correspond to typical conditions in the broad-line region, as well as in intermediate regions between the broad- and the narrow-line regions. We also found that these values correspond to electron column densities in the range $3 \times 10^{19} \leq N_e \leq 1 \times 10^{22}$ cm$^{-2}$, which are consistent with the fact that the X-ray observations do not show a significant change in column density. In Figure 13 we

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6 Calculations used an exact frequency of 5.8 GHz.
show a qualitative model for the free–free absorber. This begins with magnetic reconnection events that launch clumpy dense warm plasma, causing the drop in intensity seen in our radio observations. This phenomenon is similarly seen in X-ray binary systems; recently, Sharma et al. (2021) looked at X-ray binary system LS I + 61°303 and found it to be variable in both X-ray (0.3–10 keV) and radio (13–15.5 and 15.5–18 GHz) with a significant correlation. They suggest both emissions are due to the same electron population, but it is unknown if both emissions are caused by a singular physical process or if multiple processes contribute individually to each emission. This was observed in an optically thin flare, which is most likely due to shocks or magnetic reconnection events. Given multiple reconnection events, this can lead to multiple ejections of plasmoids of different sizes. The frequency of these events can be anywhere from minutes, to hours, and days. They can take place in the accretion disk to produce flares that have been observed in hard to soft state transitions in microquasars (as seen in GRS 1915+105). These flares eject plasmoids as single blobs that can expand almost adiabatically and that can quickly become optically thin in the radio band after leaving the accretion disk (e.g., Yuan et al. 2009), although the time frame for this process is not clearly stated.

4.1.2. Intrinsic Variability

Considering the variability transpires within 28 days, this confines the emitting region for both the (2–10 keV) X-ray and (6 GHz) radio luminosity (with X-ray variability seen in previous studies on shorter timescales of days to weeks) to within a radius of 28 light days. With the resolution of the VLBA and at these timescales, the physical mechanism for the luminosity changes must be confined to within this radius and must not be from any larger structures crossing the line of sight. This leads to the possibility the variability in the radio and X-ray emission is intrinsic for NGC 2992 and stems from the same electron population in the corona. This may explain why during the flare when the X-ray emission peaks, the radio emission drops below our detection limit. However, this does not explain why the radio emission is delayed at the beginning of the flare. In the literature there have been delays observed, but it is when the radio precedes the X-ray. In one such extreme case seen in blazar PKS 1510-089, radio emission preceded the X-ray emission by 24 days (e.g., Marscher et al. 2010). For the X-ray binary system LS I + 61°303, the radio preceded the X-ray by ~25 minutes (Sharma et al. 2021). Since our observations are in 28 day intervals, we do not have enough data to determine if the variability seen in the radio varies at the same timescales as seen previously in X-rays (days to weeks). It is possible the true delay is in fact the radio preceding the X-ray and not the X-ray leading the radio, as shown from our observations. Finally, there is also the possibility the radio and X-ray variability are unrelated and have separate physical mechanisms. Future simultaneous observations are needed in shorter intervals (weekly to twice a week) to determine which follows for NGC 2992.

5. Conclusions

To our knowledge, this is the first simultaneous X-ray and VLBI radio monitoring campaign of a nearby radio-quiet AGN. Our main conclusions are as follows:

1. We find anticorrelated core radio (6 GHz) and X-ray (2–10 keV) emission from the known X-ray variable AGN in NGC 2992. The radio emission declines by over a factor of >3, shortly after (within 28 days of) a flare in the 2–10 keV X-ray emission (by a factor of ~6). The size of the radio-emitting region is constrained by the variability and is consistent with radio emission originating within the central accretion region (<0.02 pc).

2. Given the current understanding of AGN accretion, the simultaneous X-ray and core radio behavior seen in NGC 2992 can most naturally be understood as being due to flares produced by magnetic reconnection events in the accretion disk. These flares create outbursts of Comptonizing plasma, leading to an overall brightening in hard X-rays, and some of the material enters the broad-line region, increasing free–free absorption at radio wavelengths.

We have taken care to robustly estimate the influence of the two NGC 2992 observations potentially affected by the software bug in the new Mark 6 recorders, and we included a scaling factor to correct for this issue. This scaling factor included a robustly estimated intrinsic uncertainty term that we have included in our analysis. Nonetheless, including the scaling factor and its uncertainty is the more conservative approach, and so we are confident that the radio variability we have observed in NGC 2992 is real.

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Software: Astropy (Astropy Collaboration et al. 2013, 2018), TOPCAT (Taylor 2005), AIPS (Greisen 2003), XSPEC (Arnaud 1996).

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