Observing Application

Date:	
Proposal ID:	VLA/2023-07-085
PI:	Qi Yuan
Type:	Director's Discretionary Time - Exploratory Time
Category:	Low-Luminosity AGN
Total time:	5.39

Confirming the radio property of a unique triple broad-line AGN candidate

Abstract:

Triple merger systems are extremely rare in current observations and are very important to understand galaxy evolution and supermassive black hole formation. J1423+6358 is a unique triple broad-line AGN candidate at z = 0.13 with kpc-scale separation. Its radio emission has been significantly detected by FIRST survey, wherein the morphology encompasses all three nuclei (two cores are mixed). To spatially resolve three individual nuclei and confirm the triple radio-emitting/radio-loud AGN nature, we therefore propose 5.39 hr VLA observations at L, C, S, and X bands given its high angular resolution and sensitivity. The four-band, high-quality images will provide detailed radio properties of each core (e.g., spectral index and brightness temperature) and offer an opportunity to resolve any potential extended jet structure, allowing us to explore the connections between merger and nucleus/ radio activity in galaxies.

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Related Proposals:

Joint:

Not a Joint Proposal.

Observing type(s):

Continuum

VLA Resources

Name	Conf.	Frontend & Backend	Setup
L band	A	L Band 20 cm 1000 - 2000 MHz General and Shared Risk Observing - Wideband	Basebands: 2 x 512 MHz(8-bit) Baseband centers (GHz): 1.264, 1.776 Total bandwidth (GHz): 1.0 Polarization products: Dual Dump time (s): 2.0 Data rate: 2.9 MB/s, 10.6 GB/h
S band	A	S Band 10 cm 2000 - 4000 MHz General and Shared Risk Observing - Wideband	Basebands: 2 x 1 GHz(8-bit) Baseband centers (GHz): 2.5, 3.5 Total bandwidth (GHz): 2.0 Polarization products: Dual Dump time (s): 2.0 Data rate: 5.9 MB/s, 21.1 GB/h
C band	A	C Band 6 cm 4000-8000 MHz General and Shared Risk Observing - Wideband	Basebands: 2 x 2 GHz(3-bit) Baseband centers (GHz): 5, 7 Total bandwidth (GHz): 4.0 Polarization products: Dual Dump time (s): 2.0 Data rate: 11.7 MB/s, 42.2 GB/h
X band	A	X Band 3.6 cm 8000 - 12000 MHz General and Shared Risk Observing - Wideband	Basebands: 2 x 2 GHz(3-bit) Baseband centers (GHz): 9, 11 Total bandwidth (GHz): 4.0 Polarization products: Dual Dump time (s): 2.0 Data rate: 11.7 MB/s, 42.2 GB/h

Sources

Name	Position		Velocity		Group
J1423+6358	**Coordinate system**	Equatorial	**Convention**	Redshift	triple AGN
	Equinox	J2000			
	Right Ascension	14:23:14.4	**Ref. frame**	LSRK	
		00:00:00.0			
	Declination	+63:58:03.7	**Velocity**	0.13	
		00:00:00.0			
	Calibrator	No			
1429+632	**Coordinate system**	Equatorial	**Convention**	Optical	triple AGN
	Equinox	J2000			
	Right Ascension	14:29:05.3	**Ref. frame**	Barycentric	
		00:00:00.0			
	Declination	+63:16:04.7	**Velocity**	0.00	
		00:00:00.0			
	Calibrator	Yes			

Name	Position		Velocity		Group
3C286	**Coordinate system**	Equatorial	**Convention**	Optical	triple AGN
	Equinox	J2000			
	Right Ascension	13:31:08.28	**Ref. frame**	Barycentric	
		00:00:00.0			
	Declination	+30:30:32.9	**Velocity**	0	
		00:00:00.0			
	Calibrator	Yes			

Sessions:

Name	Session time (hours)	Repeat	Separation	LST minimum	LST maximum	Elevation minimum
triple AGN	5.39	1	0 day	05:33:44	23:12:45	15

Session Constraints:

Name	Scheduling constraints	Comments
triple AGN		

Session Source/Resource Pairs:

Session name	Source	Resource	Time
triple AGN	J1423+6358 1429+632 3C286	L band	0.82 hour
triple AGN	J1423+6358 1429+632 3C286	C band	1.01 hour
triple AGN	J1423+6358 1429+632 3C286	X band	2.73 hour
triple AGN	J1423+6358 1429+632 3C286	S band	0.83 hour

Plan of dissertation: no

Technical Justification:

Combined telescopes:
NA

Array configuration:
Our target is a triple AGN system. Nuclei A and B are separated by 2.4 arcsec, and nuclei B and C are separated by 8.5 arcsec. The A-configuration achieves synthesized beam sizes of 1.395, 0.977, 0.488, and 0.293 arcsec at the L, S, C, and X bands. These performances will be sufficient to resolve three nuclei and will also be suitable for resolving any potentially extended emissions, such as a jet."

Subarrays:
NA

Future semesters:
NA

Scheduling restrictions:

1.There is no special requirement on observing at daytime or nighttime.

2.The source will peak at 60 deg and will be above 50 deg for more than 6 hours (above 20 deg for > 16 hours).

3.No constraints on scheduling.

4.NA

5.NA

LST Range Justification:

NA

Receivers requested:

We request to use the L-band(1-2 GHz), S-band(2-4 GHz), C-band(4-8 GHz), X-band(8-12 GHz) receivers. This selection will guarantee adequate resolution to resolve the three nuclei. It can decompose nucleus A and potential nucleus B at 1.4 GHz to the greatest possible extent and to ensure that the faint nucleus C can be detected at higher frequencies. Four bands are requested for better slope constrain and resolving of potentially tight core-jet morphology in high frequency.

Samplers and correlator setup:

We'll use an 8-bit digital sampler for the L and S bands and a 3-bit digital sampler for the C and X bands.

Mosaic requirements:

NA

Sensitivity:

Taking a peak flux density of 450 mJy/beam at FIRST 1.4 GHz observation, if a compact core dominates the nuclei A and B and conservatively assuming a spectral index of -1, we can estimate its flux density as 210, 105, and 63 mJy at 3, 6 and 10 GHz, respectively. To guarantee the predicted SNRs are above 30, we require the imaging sensitivities at 1.4, 3, 6, and 10 GHz should be less than 15, 7, 3.5, and 2.1 mJy/beam, respectively.

Integration time:

We used the VLA exposure calculator to estimate the requested observing time, by adopting the typical weather conditions in Autumn with 25 antennas, robust/natural weighting and a 8-bit/3-bit sampler. This yields 0.82, 0.83, 1.01, 2.73 hr integration time (0.54, 0.55, 0.60, 1.87 hr on source) for L, S, C, and X bands. Therefore, we totally request 5.39 hr for VLA A-configuration in DDT mode.

Dump time:

We are utilizing the default correlator dump time for each frequency band. This results in estimated data rates of 2.9 MB/s and 10.6 GB/h for the L band, 5.9 MB/s and 21.1 GB/h for the S band, and 11.7 MB/s and 42.2 GB/h for the C and X bands, correspondingly. Based on the integration time calculated in this proposal, the cumulative data volume amounts to approximately 184 GB.

Imaging considerations:

NA

Polarimetric considerations:

NA

RFI considerations:

A fraction of the bandwidth may be severely affected by RFI at L, S, C, and X bands. We assume that 40%,25%, 15%, and 15% of the total maximum bandwidth at L, S, C, and X bands, respectively, are affected by RFI in the above sensitivity calculations.

Joint considerations:

NA

Other:

NA

CONFIRMING THE RADIO PROPERTY OF A UNIQUE TRIPLE BROAD-LINE AGN CANDIDATE AT KPC SCALE

1 Scientific Justification

The identification of multiple supermassive black holes (SMBHs) separated by distances of approximately kiloparsecs (kpc) holds immense significance in our quest to understand galaxy evolution, SMBH formation and their co-evolution (e.g., Volonteri et al., 2003). These systems represent potential precursors to gravitationally bound multiple SMBH mergers, making them a prime target for low-frequency gravitational wave experiments such as Pulsar-Timing Arrays (Inomata et al., 2017) and the Laser Interferometer Space Antenna (Amaro-Seoane et al., 2023). Different from dual AGN systems, triple SMBH systems offer a unique opportunity to explore the intricate dynamics of three-body interactions (Blaes et al., 2002; Merritt, 2006), serving as a crucial laboratory for understanding the chaotic nature of such systems. Furthermore, these systems can provide important insights and clues in resolving the final-parsec problem related to the coalescence of binary SMBHs (e.g., Hoffman & Loeb, 2007). Finally, the radio property in multi-core system will provide crucial information about how merger process triggers the nucleus and radio activity in AGNs (e.g., Ellison et al., 2011).

Given the small projected separation in the sky, close, multiple SMBHs with separation of $\lesssim$ kpc are extremely rare in current observations. This apparent scarcity can be caused by the limited spatial resolution of the survey facilities or that they are intrinsically scarce in kpc/sub-kpc scale. To date, several hundred dual active galactic nuclei (AGN) and candidates have been discovered (Liu et al., 2011b), yet only five triple AGN candidates are known, with the lowest projected separation being below 10 kpc (Barth et al., 2008; Schawinski et al., 2011; Liu et al., 2011a, 2019). We distinguish these tight kpc-scale triple systems showing interactions from the relatively high-z triplets, whose projected separations are usually above a few tens of kpc and only physically linked by the same dark matter halo (Djorgovski et al., 2007; Farina et al., 2013; Hennawi et al., 2015; Kalfountzou et al., 2017; Yadav et al., 2021). With the advent of observations boasting higher sensitivity and angular resolution, two triple candidates, NGC 3341 (Barth et al., 2008) and J1027+1749 (Liu et al., 2011a), were found to be false positives (Bianchi et al., 2013; Benítez et al., 2023). Meanwhile, the status of two other candidates (ID 1163 and J1502+1115) remains under debate (Wrobel et al., 2014; Liu et al., 2019) due to the ambiguous observational evidence for active nuclei. Consequently, J0849+1114 stands as the most robust triple AGN system to date (a triple Seyfert 2) (Liu et al., 2019). However, all previously identified triple AGN systems at kpc scale were characterized using empirical emission-line ratio diagnostics, which is **inconclusive** because of potential confounding factors due to a mix of star formation, dust extinction, and shock heating which may mimic AGN excitation.

J1423+6358 is the first triple broad-line AGN candidate at $z = 0.13$ (see Figure 1 & 2), discovered through a systematic search of multiple AGNs by cross-matching quasars in SDSS DR14 with Gaia detections within $6''$. As shown in Figure 1, nuclei A and B are separated by 5.7 kpc ($2.4''$) and nuclei A and C are separated by 17.4 kpc ($7.3''$). Based on the spectral decomposition analysis in Figure 2, all three nuclei exhibit clear broad Hα emission, making this triple AGN system a unique case known to date with broad emission lines at kpc scale. We emphasize that the extraction of the weak but significant broad components was performed through local fitting with a single power-law, without considering any potential contributions from the host galaxy that may introduce artificial broad components. However, we still consider its candidacy putative because Type IIn SN could also produce temporary broad Balmer line (e.g., Hα) lasting for a few years (e.g., SN 2005ip, Smith et al., 2017). This scenario can be eliminated if broad C IV lines are observed in each core from the Hubble Space Telescope (HST) observations. The spectroscopic redshifts obtained suggest slight blueshifts relative to nucleus A, with radial velocity shifts of less than 200 $\mathrm{km\,s^{-1}}$, ruling out a lensing scenario, together with the different line ratios of Hα/[N II]. Most importantly, radio emission is also detected by the FIRST (Faint Images of the Radio Sky at Twenty-Centimeters) survey ($\sim$ 3 mJy in total at 1.4 GHz) in Figure 1 and flux peaks of three cores are in good agreement with the optical nuclei detected by GAIA, indicating the possibility of a triple radio-emitting/radio-loud, broad-line AGN system, which is extremely rare.

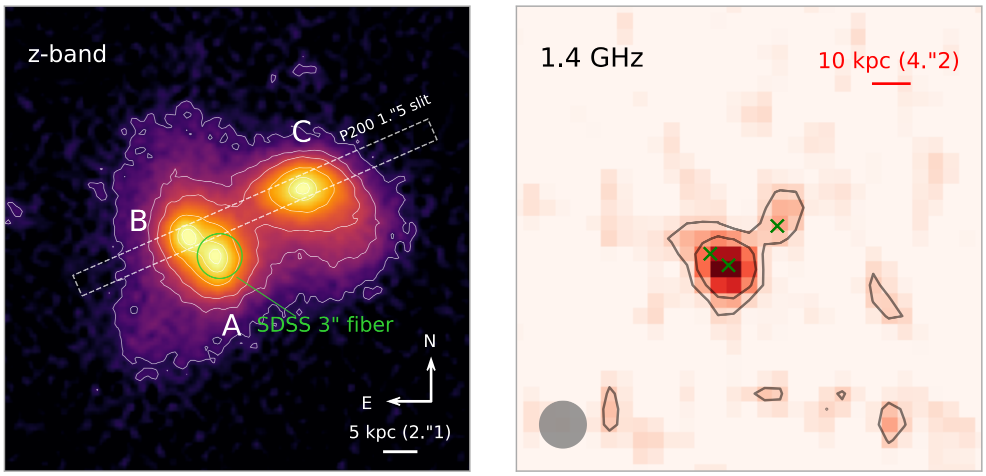

Figure 1: DECaLS optical and FIRST 1.4 GHz images for SDSS J1423+6358. Left: DECalS z band image with a $30'' \times 30''$ field of view (FOV). White box represents the location of 1.5-arcsec long slit in Palomar/P200 observations and the green circle displays the $3''$ fiber location in the SDSS observation. The first lowest projected separation between nuclei A and B is 5.7 kpc (2.4 arcsec). The second lowest separation between nuclei A and C is 17.4 kpc (7.3 arcsec). Right: FIRST 1.4 GHz image with a $120'' \times 120''$ FOV. Optical centers of three nuclei detected by GAIA are shown with the green crosses. The black contours show the flux density at 0.3 and 0.6 mJy, respectively.

2 Proposed VLA observations and scientific goals

To spatially resolve three independent cores, we request 5.39 hr Karl G. Jansky Very Large Array (VLA) observations with A-configuration in the L, S, C, and X bands, which has the best angular resolution, especially at low-frequency bands where most radio emission are reserved. The FIRST has significantly detected the moderate radio emission from this triplet (2.66 ± 0.135 mJy), and the morphology of the radio contours indicates good correspondence with optical positions although Nuclei A and B are mixed together. With the sensitivity and resolution ($\lesssim$ **1.4** arcsec) of VLA observations, we expect to detect and separate the radio emission from individual sources. Given the four-band images successfully, we are able to constrain the radio properties of each core, e.g., spectral index, brightness temperature and variability, to pin down the triple radio AGN nature. In a bigger picture of galaxy evolution and BH growth, it offers a unique case to potentially understand the association of the nucleus, jet, and star formation etc. with interaction/merger process. Furthermore, it constraints the lower limit of the occurrence of triple AGNs at kpc scale. Finally, it provides important insights about three-body interactions, the final-parsec problem, and BH-galaxy co-evolution in a merger system. Therefore, the powerful VLA observation may

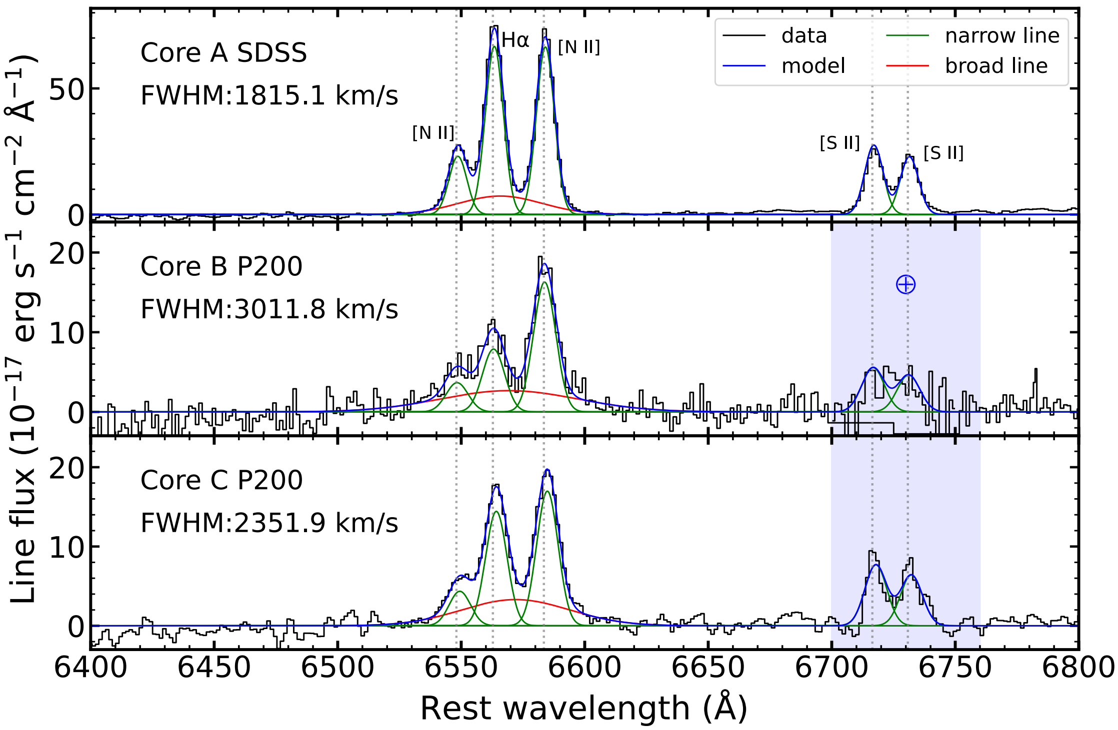

Figure 2: Spectral decomposition for the Hα region of SDSS and Palomar/P200 spectra. We performed a local fit for the rest-frame Hα region from 6400 to 6800 Å, with a single power-law accounting for the continuum emission following Shen et al. (2011). The host components are not applied in the fits to avoid introducing any artificial broad components in the host removal. All the narrow components (green line) are tied together for the central wavelength and line width. The broad Hα components (red line) are clearly shown in each spectrum, making it the first triple broad-line AGN at kpc scale. The blue shadow is the region performed telluric line correction. The Hβ region is not shown here due to the low SNR.

reveal the first triple broad-line and radio-emitting/radio-loud AGN at kpc scale, as well as secrets in galaxy merger, co-evolution and AGN activity. It is a high-risk/high-return exploratory time proposal, the outcome serves a subsequent multi-band proposal (e.g., HST and Chandra), and the final results worth a high impact journal. Other VLA configurations are unable to resolve the closest cores yet not lose the flux at low-frequency bands and waiting 16 months will significantly reduce its scientific importance due to the operation of the Euclid telescope.

3 Technical Requirements

We request VLA observations with A-configuration at L, S, C, and X bands (central frequency 1.4, 3, 6, and 10 GHz) for a total integration time of 5.39 hr before Oct 2 2023. Robust weighting is employed for L-band imaging to maximize resolution, while natural weighting is adopted for imaging in the other bands to optimize sensitivity, which achieves a synthesized beam of 1.395, 0.977, 0.488, and 0.293 arcsec at the L, S, C, and X bands with A-configuration, respectively. This aims to decompose nucleus A and potential nucleus B at 1.4 GHz to the greatest possible extent and to ensure that the faint nucleus C can be detected at higher frequencies. Four bands are requested for better slope constrain and resolving of potentially tight core-jet morphology in high frequency.

We calculate the required sensitivity according to the expected flux density of nucleus C (faintest, the flux density of nucleus B is hard to predict and we simply assume it has a similar flux density as nucleus C.). Taking a peak flux density of 450 μJy beam^{-1} at FIRST 1.4 GHz observation (see Figure 1), if a compact core dominates the nuclei A and B and conservatively assuming a spectral index of $\alpha = -1$ ($S_\nu \propto \nu^\alpha$), we can estimate its flux density as 210, 105, and 63 μJy at 3, 6 and 10 GHz, respectively. To guarantee the predicted SNRs are above 30, we require the imaging sensitivities at 1.4, 3, 6, and 10 GHz should be less than 15, 7, 3.5, and 2.1μJy beam^{-1}, respectively. Even if 2/3 of the flux is resolved out, we can still achieve an SNR of ~ 10 at each band, and a realistic flatter radio spectrum will definitely result in higher SNRs. We used the VLA exposure calculator to estimate the requested observing time, by adopting the typical weather conditions in Autumn with 25 antennas, robust/natural weighting and a 8-bit/3-bit sampler. This yields 0.82, 0.83, 1.01, 2.73 hr integration time (0.54, 0.55, 0.60, 1.87 hr on source) for L, S, C, and X bands. Therefore, we totally request 5.39 hr for VLA A-configuration in DDT mode.

References

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Array Configuration	A
Number of Antennas	25
Polarization Setup	Dual
Type of Image Weighting	Robust
Representative Frequency	1.4000 GHz
Receiver Band	L
Approximate Beam Size	1.395"
Digital Samplers	8 bit
Elevation	Medium (25°-50°)
Average Weather	Autumn
Calculation Type	Time
Time on Source	0h 32m 24s
Total Time	0h 49m 25s
Frequency Bandwidth	0.6000 GHz
Line Velocity Width	128,482.4820 km/s
RMS Noise (units/beam)	14.5000 μJy
RMS Brightness (temp)	4.6437 K
RMS H I Column Density	1.08766E+24
Confusion Level	0.0000 Jy

Overhead. Short low-frequency observations: overhead calculated as T_oh = 0h 17m 1.04s = 0.124 * 0h 32m 23.85s + 0h 13m 0s, with the fixed overhead consisting of an initial slew of 0h 11m 0s and a fixed calibration overhead of 0h 2m 0s.

Severe RFI effects. At this frequency band, part of the selected bandwidth may be severely affected by RFI. Visit the following web page for the RFI information at the VLA: https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/rfi Of the 1-2 GHz frequency span of the L-band, up to 40% could be affected by RFI. This should be properly accounted for while estimating the rms noise.

Produced by the NRAO EVLA Exposure Calculator (2023 June).

Array Configuration	A
Number of Antennas	25
Polarization Setup	Dual
Type of Image Weighting	Natural
Representative Frequency	3.0000 GHz
Receiver Band	S
Approximate Beam Size	0.977"
Digital Samplers	8 bit
Elevation	Medium (25°-50°)
Average Weather	Autumn
Calculation Type	Time
Time on Source	0h 32m 56s
Total Time	0h 50m 1s
Frequency Bandwidth	1.5000 GHz
Line Velocity Width	149,896.2290 km/s
RMS Noise (units/beam)	6.5000 μJy
RMS Brightness (temp)	0.9252 K
Confusion Level	0.0000 Jy

Overhead. Short low-frequency observations: overhead calculated as T_oh = 0h 17m 5.05s = 0.124 * 0h 32m 56.18s + 0h 13m 0s, with the fixed overhead consisting of an initial slew of 0h 11m 0s and a fixed calibration overhead of 0h 2m 0s.

Severe RFI effects. At this frequency band, part of the selected bandwidth may be severely affected by RFI. Visit the following web page for the RFI information at the VLA: https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/rfi Of the 2-4 GHz frequency span of the S-band, up to 25% could be affected by RFI. This should be properly accounted for while estimating the rms noise.

Produced by the NRAO EVLA Exposure Calculator (2023 June).

Array Configuration	A
Number of Antennas	25
Polarization Setup	Dual
Type of Image Weighting	Natural
Representative Frequency	6.0000 GHz
Receiver Band	C
Approximate Beam Size	0.488"
Digital Samplers	3 bit
Elevation	Medium (25°-50°)
Average Weather	Autumn
Calculation Type	Time
Time on Source	0h 36m 14s
Total Time	1h 0m 18s
Frequency Bandwidth	3.4000 GHz
Line Velocity Width	169,882.3929 km/s
RMS Noise (units/beam)	3.5000 μJy
RMS Brightness (temp)	0.4982 K
Confusion Level	0.0000 Jy

Overhead. Short low-frequency observations: overhead calculated as T_oh = 0h 24m 3.19s = 0.305 * 0h 36m 14.40s + 0h 13m 0s, with the fixed overhead consisting of an initial slew of 0h 11m 0s and a fixed calibration overhead of 0h 2m 0s.

Severe RFI effects. At this frequency band, part of the selected bandwidth may be severely affected by RFI. Visit the following web page for the RFI information at the VLA: https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/rfi Of the 4-8 GHz frequency span of the C-band, up to 15% could be affected by RFI. This should be properly accounted for while estimating the rms noise.

Produced by the NRAO EVLA Exposure Calculator (2023 June).

Array Configuration	A
Number of Antennas	25
Polarization Setup	Dual
Type of Image Weighting	Natural
Representative Frequency	10.0000 GHz
Receiver Band	X
Approximate Beam Size	0.293"
Digital Samplers	3 bit
Elevation	Medium (25°-50°)
Average Weather	Autumn
Calculation Type	Noise/Tb
Time on Source	1h 51m 56s
Total Time	2h 43m 53s
Frequency Bandwidth	3.4000 GHz
Line Velocity Width	101,929.4357 km/s
RMS Noise (units/beam)	2.1000 μJy
RMS Brightness (temp)	0.2989 K
Confusion Level	0.0000 Jy

Overhead. Standard observations: overhead calculated as T_oh = 0h 51m 56.38s = 0.464 * 1h 51m 56.34s.

Severe RFI effects. At this frequency band, part of the selected bandwidth may be severely affected by RFI. Visit the following web page for the RFI information at the VLA: https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/rfi Of the 8-12 GHz frequency span of the X-band, up to 15% could be affected by RFI. This should be properly accounted for while estimating the rms noise.

Produced by the NRAO EVLA Exposure Calculator (2023 June).