Radio Telescope Observations of the April 8, 2024, Total Solar Eclipse at 1420 MHz

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Abstract. We present radio telescope observations of the April 8th, 2024, total solar eclipse from the University of Central Arkansas campus in Conway, Arkansas, using a 2.3-m SPIDER 230C parabolic radio telescope tuned to a frequency of 1420 MHz. Observations began approximately 19 min before first contact and ended approximately 2.5 min after fourth contact, continuously tracking the sun across the sky. Our radio observations show a reduction in relative intensity from the beginning of the lightcurve to the middle of totality of approximately 70%, indicating that the apparent size of the radio solar disk was larger than the apparent size of the moon and therefore only partially covered. This contrasts with optical data, where the eclipse was total. To determine the relative size of the radio solar disk, we compared our observed radio and optical data to theoretical lightcurves of the eclipse with different solar radii. From our analyses, we found that the radio solar disk is approximately $R_{1420} = 1.27R_{\odot}$. This is consistent with previously published results.

INTRODUCTION

Our goal with this project was to determine the apparent size of the sun using 1420-MHz radio telescope observations taken during the April 8th, 2024, total solar eclipse. At this frequency, the radio emission from the sun is dominated by gyroresonance emission from electrons spiraling in the sun's extended magnetic field, which make the sun appear larger in radio frequencies than at optical frequencies. We collected data in both the optical and radio frequencies, which provided a unique opportunity to compare the relative sizes in the optical and radio spectra. To accomplish this, we needed to determine how much of the solar disk was obscured by the moon during totality in both the optical and radio wavelengths. We had only one source of radio lightcurve data: UCA's 2.3-m radio telescope. In order to compare the radio eclipse to the optical eclipse, we had two sources of optical lightcurve data: a livestream from the UCA Observatory and a broad-spectrum light sensor pointed at the sky. We also generated theoretical lightcurves using the software `Stellarium` [1] and the JPL Horizons On-Line Ephemeris System [2]. Using these data, we compared the optical and radio lightcurves to determine the relative size of the radio solar disk.

OBSERVATIONS

The Radio Lightcurve

Radio observations took place on April 8th, 2024, at the University of Central Arkansas campus in Conway, Arkansas, at approximately 35°04'51"N 92°27'36"W with an elevation of 94 m. We began collecting data at 2460409.2186657293 JD and ended at 2460409.3424835186 JD, or 2024-04-08 17:14:53 UTC and 2024-04-08 20:13:11 UTC. The telescope was a Spider 230C radio telescope with a 2.3-m parabolic dish tuned to 1420 MHz. During observation, we encountered minimal cloud cover and no sustained winds. Despite this, we did have three sources of error: A strong gust of wind pushed the telescope off target for a few seconds, an issue with the accuracy of our polar alignment caused the telescope to be slightly off target by the end of observation, and local sources of interference introduced noise into the signal. A number of data analysis methods were used to address these errors.

In our raw radio data, the brightness of the sun after fourth contact was less than the same period just before first contact. This indicated that the tracking had become inaccurate. We assume that this tracking error caused the radio intensity to decrease linearly with time. To create this linear adjustment function, we found the slope between a point around 2 min before first contact and a point around 2 min after fourth contact. The sign was then flipped on the slope and combined with the x value of the point at first contact in point slope form. This function was added to the lightcurve to adjust for the tracking error.

Our choice to smooth the data came from the need to reduce noise/random spikes and get a better idea of the shape of the curve. We chose to apply a Savitzky-Golay filter [3] to do this. This popular filtering method was used because of the lack of edge effects, letting the filter be applied over the entire lightcurve.

Normalization is the process by which the data of a graph is scaled by a constant such that the highest points are equal to 100, essentially making the data a percentage of its highest value. This is done after smoothing to avoid issues with noise spikes. Converting the analog to digital unit (ADU) counts to a relative brightness makes it possible to compare with the optical lightcurves. The smoothed and normalized data can be seen in Fig. 1.

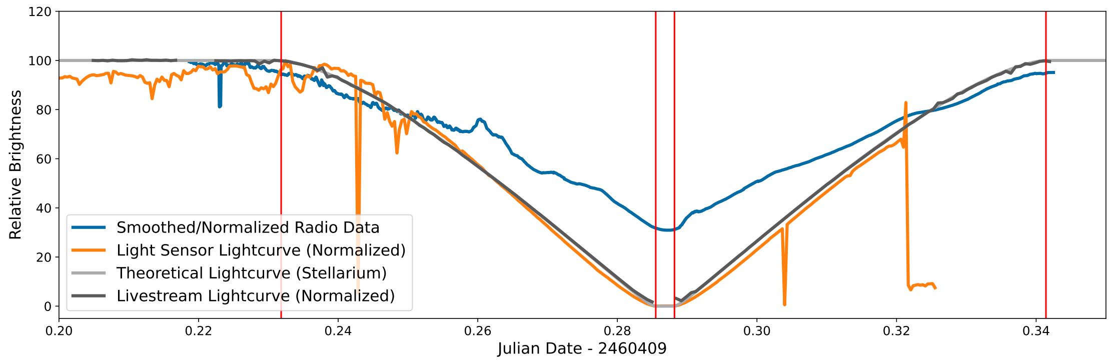


FIGURE 1. A comparison of the smoothed/normalized radio lightcurve, the normalized optical lightcurve generated from the livestream, the lightcurve generated from the light sensor, and a theoretical lightcurve generated from the software `Stellarium`. Vertical lines show first through fourth contact. The drop in the smoothed/normalized radio brightness due to the gust of wind is visible just after JD 2460409.22.

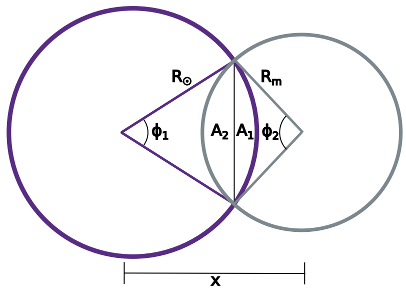
The Optical Lightcurve

To better understand the features of our radio data, we needed an optical lightcurve for comparison. Ideally, the optical lightcurve would be observed from the same location as our radio telescope in order for us to compare contact times, the depth of the eclipse, and the shape of the lightcurve. Fortunately, Dr. Scott Austin used the UCA observatory across the street from our location to livestream the eclipse using a solar filter-equipped camera mounted to the observatory telescope. Another experiment near our location, led by Dr. Todd Abel and UCA student Shane Ayotte, used a Vernier Light Sensor (LS-BTA) pointed straight up at the sky to measure overall sky brightness.

The livestream of the solar eclipse was captured by Austin using a Sony Alpha 6400 camera with a Sony FE 24-240mm f/3.5-6.3 lens and NiSi Solar Filter Pro Nan UV/IR Cut ND 100000 72-mm filter. This solar filter was removed during totality, marked by vertical lines at 2460409.2849 JD and 2460409.2884 JD. This setup was attached to a Meade-14 LX200R on a Paramount MX+ equatorial mount to track the sun across the sky. To transform the livestream into a lightcurve, we needed to extract the percentage of the sun's disk visible in the video frames as the eclipse progressed. We accomplished this by first grayscaling the image of the eclipse and then using Otsu thresholding [4] to count pixels above a certain value. To get the time for each data point, we took an image of the in-video clock at the same time we counted the pixels and used computer vision to recognize the characters in the clock. The number of pixels of the solar disk over time were then normalized to a relative brightness.

The light sensor used to collect data during the solar eclipse was a Vernier Light Sensor (LS-BTA) pointed at the sky. Abel and Ayotte provided the light sensor data, which we normalized to relative brightness. Because the light sensor data had timestamps included, we used them to confirm the timing accuracy of our other lightcurves.

Figure 1 shows the observed lightcurves and a theoretical lightcurve generated from the software `Stellarium`, where we observed that all three optical lightcurves had a very similar shape with heavy overlap between the theoretical and livestream lightcurves. This implies that our optical lightcurves are accurate and can be compared with our radio lightcurve to determine the size of the sun's radio emission.



$$A_1 = \frac{1}{2} R_\odot^2 (\phi_1 - \sin\phi_1) \tag{1}$$

$$A_2 = \frac{1}{2} R_m^2 (\phi_2 - \sin\phi_2) \tag{2}$$

$$\phi_1 = 2\cos^{-1}\left(\frac{R_\odot^2 - R_m^2 + x^2}{2R_\odot x}\right) \tag{3}$$

$$\phi_2 = 2\cos^{-1}\left(\frac{x^2 - R_\odot^2 + r_m^2}{2R_m x}\right) \tag{4}$$

FIGURE 2. The geometric relationships used to calculate the obscuration of the sun. The percentage of obscuration is found by dividing the combined area $A_1 + A_2$ by the apparent area of the sun's disk $\pi R_\odot^2$.

THEORETICAL MODELS

Stellarium

To check the validity of our livestream-derived optical lightcurve, we needed to find the expected eclipse obscuration percentage over time for our location. We used the free, open-source planetarium software `Stellarium` [1] to achieve this. After setting the time, date, and location of our radio telescope in `Stellarium`, we queried the software's API to step the simulation forward in time and extracted the eclipse percentage for 1000 points in time, starting before first contact and ending after fourth contact. The resulting theoretical lightcurve was then overlaid on the eclipse obscuration derived from the UCA Observatory livestream. The agreement between the two is excellent, as shown in Fig. 1.

Theoretical Lightcurve Comparison

To determine the apparent radius of the sun at 1420 MHz, we compared our observed radio lightcurve to a series of theoretical lightcurves where the radius of the sun differs. To accomplish this, we first downloaded high-accuracy ephemeris data from the JPL Horizons On-Line Ephemeris System [2]. Using the angular radii of both the sun and moon, along with the angular separation between the two, we calculated the obscured area of the solar disk at 2000 points in time during the eclipse using the geometric relationships and Eqs. (1)–(4) shown in Fig. 2.

We found that the radio lightcurve reached a minimum of 30.9% of the total solar flux during totality. Using these relationships, we were able to create theoretical lightcurves for varying solar radii from $R = 1.0R_\odot$ to $R = 1.45R_\odot$. We found the best-fitting solar radius by manually adjusting the model until the difference between the observed and model minima dropped below 1%. These theoretical lightcurves are compared with the radio lightcurve in Fig. 3. Although our best-fit model matches the observed dip in brightness, it fails to match the slope of the observed lightcurve before and after totality and does not show the flat bottom expected while the moon transits the larger solar disk. The theoretical curves assume a uniform disk brightness, not accounting for limb darkening, sunspots, radio emission from the corona, or other solar activity. Despite these variances, we found that the best-fit curve has an apparent solar radius of $R_{1420} = 1.27R_\odot$. This lies between the results of $R_{1420} = 1.14R_\odot$ found by [5], and $R_{1420} = 1.4R_\odot$ found by [6]. Both of these references observed partial solar eclipses at 1420 MHz. In the case of [6], those observations were made with the same radio receiver and software used in this study.

Our results are consistent with the trend found in [7], which compared decades of solar radio observations taken at many wavelengths and found that solar radius increased as the radio frequency decreased. This was also seen in the results of [5], a study that observed an eclipse at four wavelengths and found a similar trend.

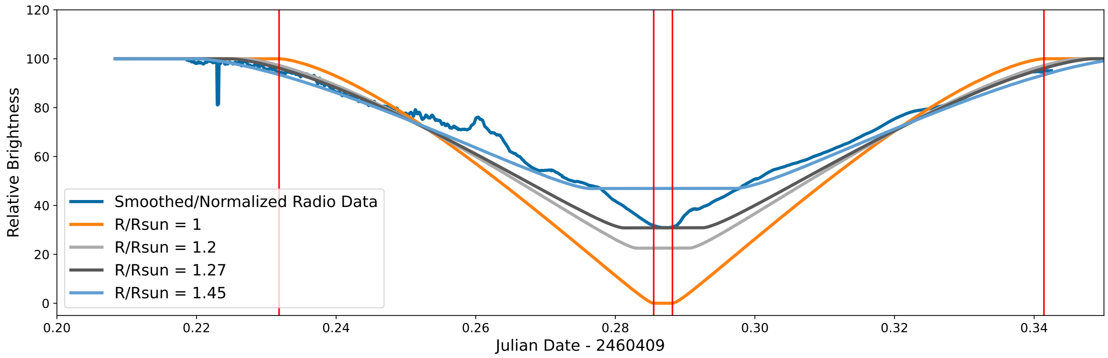


FIGURE 3. A comparison of the smoothed/normalized radio lightcurve and theoretical lightcurves generated with the JPL Horizons ephemeris data. Our best fit to the depth of the radio lightcurve has an apparent solar radius of $1.27R_{\odot}$.

CONCLUSION

Based on our comparison of data from a 2.3-m radio telescope, a broad-spectrum light sensor, an optical livestream, and theoretical data from `Stellarium` and JPL Horizons, our expectation that the radio solar disk is larger than the optical solar disk is supported. This analysis found that the best-fit curve has an apparent solar radius of $R_{1420} = 1.27R_{\odot}$, falling between the results of other studies [5] and [6]. In future work, we hope to examine the radio lightcurve in detail with the goal of analyzing the variance seen between our model slope and the recorded radio data. In a previous study [5], the slopes also differ, but not to the degree seen in our data. In [5], that variance is used to map radio emission from the sun's surface as features are eclipsed by the moon's edge moving across the face of the sun, something we hope to replicate in a future study.

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