Long-Term Meter Wavelength Variability Study of Blazar J1415+1320 Using the Ooty Radio Telescope

Sravani Vaddi, P. K. Manoharan, and D. Anish Roshi

Abstract – J1415+1320 is a well-studied blazar that exhibits strong flux density variability at a wide range of radio frequencies (2.4 GHz to 230 GHz). In this article, we present a variability study of this source at 327 MHz using data obtained with the Ooty Radio Telescope during the period 1989 to 2018. Two significant flares were detected, at epochs 2007.6 and 2008.6. These flares are also seen in the publicly available 15 GHz and 37 GHz light curves, but with a lead time of a few months. The fractional changes in the flux densities are larger at frequencies $>$ 15 GHz compared to those at 327 MHz, and during these flares the spectral indices of the increased flux densities are flatter than the quiescent spectrum. These observed features are consistent with a model of a uniformly expanding cloud of relativistic electrons or the shock-in-jet model. Our 327 MHz data set also overlaps with a rare form of variability—symmetric achromatic variability (SAV)—seen at higher frequencies ($>$15 GHz) toward the source. SAV is possibly due to gravitational milli-lensing of the core emission by an intervening massive object, and is expected to be detected at all frequencies. No variability in association with the SAV events is seen in the 327 MHz data set; however, if SAV is due to the lensing of core emission alone, then the expected variability is less than 3σ uncertainty in our measurements.

1. Introduction

J1415+1320, a BL Lac object, has allured astronomers for a very long time thanks to its controversial properties. Some of these properties include: 1) the apparent yet rare association of the active galactic nuclei (AGN) with an optical spiral host [1]; 2) detection of a counterjet in a blazar-type AGN [2]; and 3) its association to the class of compact symmetric objects as well as blazars [3]. Some of these controversies were addressed in [4], which concluded that J1415+1320 is actually a background object in the redshift range $0.247 < z < 0.5$ and is not associated with the previously known spiral host.

The radio very-long-baseline interferometry structure of J1415+1320 shows a two-sided, bent core-jet structure of size approximately 110 mas ($<$1 kpc). The core has an inverted spectrum ($\alpha > 1$) at frequencies between 1.4 GHz and 15 GHz [3]. At frequencies above 15 GHz, where the core emission dominates [4], the core has a flat spectrum ($\alpha \approx 0.001$) (estimated using 15 GHz and 37 GHz flux densities). The spectrum of the jet and the counterjet are generally steep ($\alpha < -1$) but vary from being flat at the knots to steep in the more diffused region [3]. The total flux density of the source at 1.4 GHz is approximately 1 Jy, dominated by emission from the jets, and it increases to 8 Jy at 80 MHz [5].

The source exhibits strong variability in its radio light curve [6]. Variability in an AGN reveals crucial information about the size, structure, and dynamics of the radiating source, down to scales that otherwise need extremely long-baseline interferometers. While variability in a source is a complicated feature that is not yet fully understood, several possible mechanisms are discussed in the literature, broadly categorized into intrinsic and extrinsic phenomena. Intrinsic variability occurs due to (but not limited to): 1) shock waves forming and propagating relativistically along the jets [7]; 2) magnetohydrodynamic instabilities in the jet [8]; 3) variation in relativistic beaming as a result of viewing-angle change in a twisted or bent jet [9]; or 4) magnetic reconnection in turbulent jets [10]. Variability is also observed owing to extrinsic phenomena, such as refractive interstellar scintillation caused by large-scale irregularities in the interstellar medium [11].

An interesting aspect of the radio light curve of J1415+1320 is that it displays a hitherto unrecognized form of variability, referred to as symmetric achromatic variability (SAV) [6]. This variability is seen as a U-dip feature in the light curve, and is time-symmetric and achromatic over 15 GHz to 234 GHz. This rare variability is possibly due to gravitational milli-lensing of the compact core emission in J1415+1320 by an intervening $10^2\ M_\odot$ to $10^5\ M_\odot$ mass condensates [6].

So far most of the variability studies of J1415+1320 have been made at frequencies $\geq$ 2.4 GHz. In this article, we present long-term (1989.8 to 2017), low-frequency (327 MHz) flux density observations of J1415+1320 taken using the Ooty Radio Telescope (ORT), operated by the Radio Astronomy Centre, Tata Institute of Fundamental Research, India [12]. The details of observations and data reduction are given in Section 2. We report radio flux density variation of J1415+1320 at 327 MHz in epochs 2007.6 and 2008.6. Further, we use the data to investigate the achromatic nature of two previously

Manuscript received 17 December 2021.

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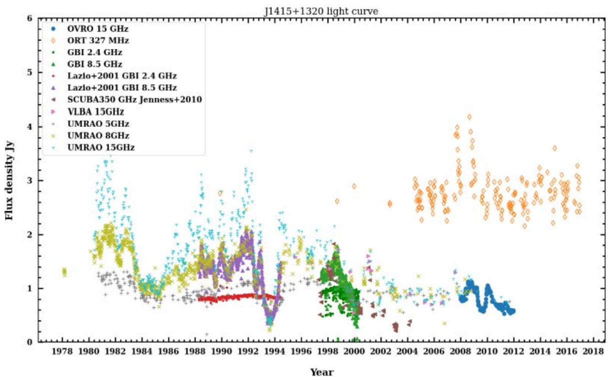

Figure 1. Radio light curve of J1415+1320 at different frequencies taken from the literature together with the ORT data. The data were compiled from the following: 1) Owens Valley Radio Observatory [15]; Green Bank interferometer [16]; submillimeter common-user bolometer array [17]; very-long-baseline array [18]; and the University of Michigan Radio Astronomy Observatory [19].

reported SAV events down to 327 MHz, discussed in Section 3. The origin of the reported flux density variation is discussed in Section 4, and our main conclusions are given in Section 5.

2. Data

The data presented here comes from the extensive interplanetary scintillation (IPS) observations made with the ORT during the period 1989 to 2018. About 100 compact radio sources of angular size < 250 mas were observed per day at 327 MHz as part of the IPS campaign. The main purpose of these IPS observations was to investigate the three-dimensional distributions of the solar wind density, turbulence, and speed at short time intervals of a few days as well as in different phases of solar activity [13, 14]. The IPS measurements on each source were made within the solar elongation range of about $\varepsilon \approx \pm 60°$ with respect to the sun, over an observing period of about 4 months. Typically a source was observed for about 2 min to 3 min, and the same source was likely observed more than once in a day at different hour-angles. Each observing session also included observations of several flux density calibrators distributed almost uniformly between the start and end of the session.

In this article, the large IPS database was used to study the variation of the total flux density of J1415+1320 over many years. The data for J1415+1320 and the control source B1345+125 are made available online in VizieR.

3. Results

Figure 1 shows the radio light curves of J1415+1320 spanning nearly 40 years (1978 to 2018). The data at several frequencies ranging from 2.4 GHz to 350 GHz were compiled from various monitoring programs found in the literature [15–19]. The source exhibits variability at all frequencies. Strong variability

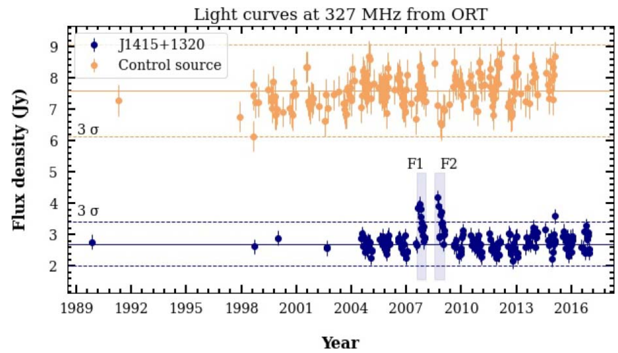

Figure 2. 327 MHz light curve of J1415+1320 (blue) and the control source B1345+125 (orange) obtained from ORT IPS measurements. The solid line and dashed line mark the mean and 3σ standard deviation. F1 and F2 mark the flares at epochs 2007.6 and 2008.6, respectively.

is seen at higher frequencies compared to lower frequencies. The variability features seen at 15 GHz are followed at 8 GHz and 5 GHz, albeit at a lower level. Further, for the 15 GHz wave band, the strength of variability generally decreases over time.

We have included the 327 MHz radio light curve over the period 1989.8 to 2017 in Figure 1 for comparison. The data used for the 327 MHz light curve contain 1953 individual observations, which were obtained after excluding observations taken at small solar elongations (i.e., $\varepsilon \leq 5°$), to avoid confusion caused by the telescope side lobe pointing at the sun. Each data point represents the average of nearly 10 to 15 consecutive observations taken around an epoch (a few days). For years 1989, 1998, 1999, and 2002, the available number of observations is limited to only about 10, and their average is plotted.

In Figure 2, we reproduce the 327 MHz light curve of J1415+1320 along with the flux density measurements of the control source B1345+125. The control source B1345+125 is a compact (<100 mas) steep spectrum source [20], monitored during a similar time period of observation as J1415+1320. The angular distance of the control source from J1415+1320 is about 10°. Both sources display strong IPS (scintillation index of the order of unity [13, 21]) and so the long-term epoch-to-epoch variations in both sources are dominated by scintillation. In other words, the normalized χ^2 variability test as defined in [22] gives a value close to unity when applied to the two data sets. The flux density of J1415+1320, interestingly, shows a significant increase at epochs 2007.6 and 2008.6 (see Figure 2); we refer to these flares as F1 and F2, respectively. The mean flux density of J1415+1320, estimated after excluding the data from the two epochs 2007.6 and 2008.6, is 2.70 Jy and the standard deviation σ of flux density variation is 0.23 Jy. During flare F1, the flux density increased rapidly from 2.66 Jy to 3.99 Jy, and during F2 it increased from 2.9 Jy to 4.19 Jy—an increase of approximately 45%. No variation in flux density is observed on the control source B1345+125;

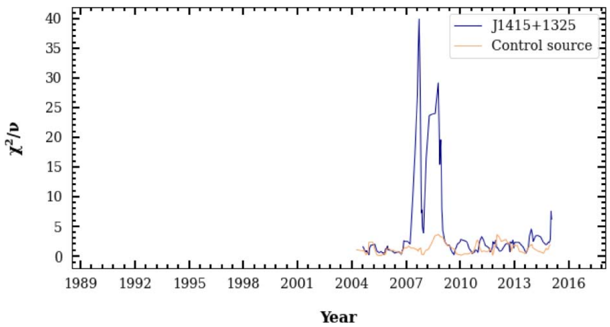

Figure 3. The χ^2 test statistic normalized by the degrees of freedom (ν) plotted for different epochs (see text).

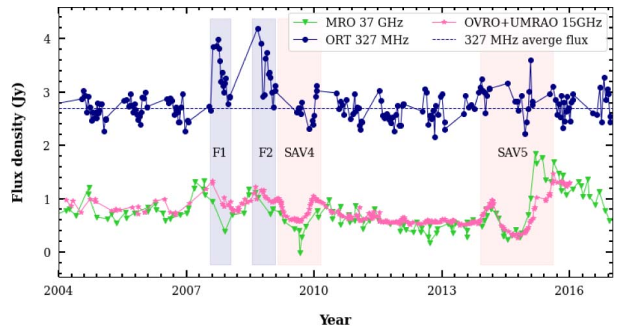

Figure 4. 327 MHz, 15 GHz, and 37 GHz light curves (from OVRO, University of Michigan Radio Astronomy Observatory, and Metsähovi Radio Observatory) of J1415+1320 covering the period 2004 to 2017. The two flares are indicated by shaded regions F1 and F2, and the two SAVs found in the 15 GHz light curve and reported in [24] are marked as shaded SAV4 and SAV5 following the notation there.

the mean and standard deviation for the control source are 7.6 Jy and 0.5 Jy, respectively. The absence of flux density variation in the control source around epochs 2007.6 and 2008.6 rules out any instrumental effects or IPS causing the variation in the flux density of J1415+1320.

The maximum flux densities during flares F1 and F2 are 3.85 Jy (17σ) and 4.19 Jy (18σ), respectively. We performed χ^2 tests on the target and the control source to further quantify the significance of the flares. Figure 3 shows the χ^2 test statistic per degree of freedom as a function of epoch. We define the χ^2 statistic $\chi^2 = \sum_{i=1}^{N} \frac{(S_i - \bar{S})^2}{\sigma_i^2}$, where S_i and σ_i are the flux density and corresponding measurement error at the ith epoch and $\bar{S}$ is the mean flux density. The magnitude of σ_i is determined by the IPS and is equal to the standard deviation (0.23 Jy) of the flux density variation away from the flares. The mean flux density already estimated is $\bar{S} = 2.7$ Jy. In Figure 3, χ^2 is computed for the data points in a moving window with $N = 4$ values and plotted against the epoch. The value is $>$10 during the flares, and the p value is < 0.003. Thus we conclude that the flares detected at 2007.6 and 2008.6 in the J1415+1320 radio light curve at 327 MHz are statistically significant.

Figure 4 shows a close-up of the radio light curve from epoch 2004 to epoch 2017. The flares F1 and F2 are marked. During the first flare F1, the flux density increases rapidly from 2.66 Jy to 3.99 Jy (a variation of 1.33 $\pm$ 0.22 Jy) in 4 days (all times given relative to the observer). The flux density falls gradually over the next approximately 84 days and reaches a low of 2.78 Jy on 2007.97. The second flare F2 is observed on 2008.67, when the flux density increases to 4.19 Jy. Unfortunately, no observations are present after the decay of the first flare and the onset of the second flare, so we are unable to estimate the rise time of this flare. The flux density of F2 falls in about 134 days and returns to 2.71 Jy on 2009.03. During F2, there is an abrupt fall in the flux density from 3.91 Jy to 2.92 Jy (variation $> 3\sigma$) on 2008.82. This lasts for about 11 days and then increases to 3.63 Jy on 2008.85.

4. Discussion

4.1 Flares F1 and F2

We compare our data with available observations at higher frequencies. We find light curves in 15 GHz OVRO data and 37 GHz Metsähovi Radio Observatory monitoring-program data overlapping with our low-frequency observations. Figure 4 shows light curves measured at these high frequencies. An event with a rapid increase followed by a gradual decay nearer to the epochs of F1 and F2 is seen in the higher frequency light curves. The peak of the flare F1 at 327 MHz occurs approximately 115 days after the epoch, when the flux density peaks at 37 GHz. The time delay between 327 MHz and 15 GHz flares is approximately 49 days. For F2, the time delays are approximately 15 days and 73 days relative to 15 GHz and 37 GHz flux density maxima.

The fractional increase in flux densities at higher frequencies is approximately 80% for both the flares—more than 1.6 times the flux density increase obtained from the 327 MHz data. Also, the decay time scale at higher frequencies is larger by a factor of approximately 2 compared to the decay time scale observed at 327 MHz. Further, the spectrum of the increased flux density between 327 MHz and 15 GHz is flatter ($\alpha =$ –0.2) than the quiescent flux density spectrum ($\alpha =$ –0.3; see Figure 5). For frequencies above 15 GHz, the increased flux density and quiescent values have similar spectral indices (see Figure 5). All these indicate that the flares might have originated outside the optically thick region of the source; the steepening of the flux density at 327 MHz during the quiescent state is due to increased contribution from the jet (and/or counterjet) in J1415+1320 [3]. The observed flux density variation and the time evolution of the flare are generally consistent with a uniformly expanding cloud of relativistic electrons or the shock-in-jet model [19, 23].

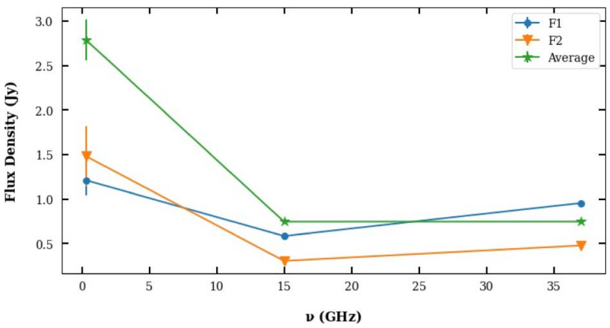

Figure 5. Spectrum of the increased flux density during the flares F1 and F2—that is, the difference between maximum (representing the peak of the flare) and minimum (representing the quiescent state) flux density—and the average flux density.

4.2 Symmetric Achromatic Variability

The flux density measurements at 327 MHz overlap with two SAV events identified at higher frequencies (>15 GHz) by [6]. These events are marked in Figure 4 as SAV4 and SAV5, following the notation from [24]. The SAV events can be seen as a U-dip feature in the 15 GHz and 37 GHz light curves. No variability of flux density within ± 0.7 Jy (3σ) is seen at 327 MHz during these two SAV events.

SAV is possibly due to gravitational milli-lensing of the compact core emission by intervening mass condensates [6, 24]. Therefore, the variability is expected to be achromatic and would have been seen in the 327 MHz data. The spectral index of the core component is inverted, with $\alpha = +1.7$ [3]. Thus the expected core flux density at 327 MHz is 1.2 mJy, and the fractional change of approximately 80% inferred from higher frequency light curves during the SAV event is much smaller than the measurement uncertainty of flux density at 327 MHz. Thus the lack of detection of any variability at 327 MHz is consistent with the gravitational lensing model proposed to explain SAV.

5. Conclusion

We studied the 327 MHz multiepoch data of J1415+1320, a blazar known for its high variability at higher frequencies. The total flux density time series was obtained from the IPS database from the ORT and covers the period between 1989 and 2018, although many of the data points are from after 2004. We report significant variability at two epochs—2007.6 (flare F1) and 2008.6 (flare F2)—and establish the significance of these flares through statistical analysis. During these flares, the flux density rises rapidly, reaches a maximum, and then decreases gradually. Both F1 and F2 are seen in the overlapping data sets at 15 GHz and 37 GHz, but with a time delay of a few months. The spectral index of the increased flux density during the flare is flatter than the quiescent spectral index, indicating that the flare is likely to be associated with activity in a region with smaller optical depth. Our data set also overlaps with two SAV events (SAV4 and SAV5) identified by [6, 24]. No variability of flux density is seen within ± 0.7 Jy (3σ) at 327 MHz during these events. Our lack of detection of variability is consistent with a gravitational lensing origin for the SAV events if only the core flux density is affected by the lensing phenomenon.

6. Acknowledgments

Thanks to the anonymous referee for insightful suggestions which helped improve the manuscript. We acknowledge the staff of the Radio Astronomy Centre, Ooty, for their help during the observations. This research made use of data from the University of Michigan Radio Astronomy Observatory, which has been supported by the University of Michigan and by a series of grants from the National Science Foundation, most recently AST-0607523.

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