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Optical and radio astrometry of the galaxy associated with FRB 150418

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ABSTRACT

A fading radio source, coincident in time and position with the fast radio burst FRB 150418, has been associated with the galaxy WISE J071634.59−190039.2. Subsequent observations of this galaxy have revealed that it contains a persistent, but variable, radio source. We present e-Multi-Element Radio Linked Interferometer Network, Very Long Baseline Array, and Australia Telescope Compact Array radio observations and Subaru optical observations of WISE J071634.59−190039.2 and find that the persistent radio source is unresolved and must be compact (<0.01 kpc), and that its location is consistent with the optical centre of the galaxy. We conclude that it is likely that WISE J071634.59−190039.2 contains a weak radio active galactic nucleus.

Key words: stars: neutron – pulsars: general – galaxies: active.

1 INTRODUCTION

Fast radio bursts (FRBs; see e.g. Petroff et al. 2016 and references therein) are millisecond-duration bursts of radio emission that have been observed at the Parkes, Arecibo, and Green Bank radio telescopes (Lorimer et al. 2007; Spitler et al. 2014; Masui et al. 2015). FRBs have dispersion measures (DMs), a measure of the electron column density, that range from 1.4 to 33 times the maximum Galactic contribution (Cordes & Lazio 2002), thought to be attributable to free electrons in the intergalactic medium. With this interpretation the distances to FRBs are cosmological (Lorimer et al. 2007; Thornton et al. 2013), and the corresponding luminosities of the FRB signals are thus many orders of magnitude higher than typical pulsar luminosities.

Non-cosmological explanations have been put forward (e.g. Burke-Spolaor et al. 2011; Kulkarni et al. 2014; Loeb, Shvartzvald & Maoz 2014) but a cosmological interpretation remains favoured, based on current observational evidence. While the extragalactic interpretation of FRBs currently prevails, their progenitor(s) are as yet unknown. In an effort to determine the nature of FRBs, the Survey for Pulsars and Extragalactic Transients (SUPERB) performs real time FRB searches at the Parkes telescope, and employs an array of multiwavelength telescopes to follow up FRB discoveries. Multiwavelength follow-up of FRB 150418 led, for the first time, to the detection of a fading radio source that was associated with a galaxy at $z = 0.49$ (Keane et al. 2016). This galaxy is also detected in the mid-infrared by *Wide-field Infrared Survey Explorer* (*WISE*; Wright et al. 2010) and catalogued as WISE J071634.59−190039.2.

Radio imaging observations of WISE J071634.59−190039.2 with the Australia Telescope Compact Array (ATCA) showed a source declining by a factor of ∼3 in brightness at 5.5 GHz during the first 6 d after the FRB. This source subsequently settled at a persistent brightness of approximately 100 μJy beam^{-1}. Comparing this behaviour to the results of transient surveys (Bell et al. 2015;

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Table 1. Radio and optical positions for WISE J071634.59−190039.2. The uncertainties of the Subaru positions have the uncertainty in the astrometric calibration added in quadrature.

Telescope	Band	α_{J2000}	δ_{J2000}
e-MERLIN	L	$07^h16^m34\overset{s}{.}554(2)$	$-19°00'39\overset{''}{.}42(5)$
e-MERLIN	C	$07^h16^m34\overset{s}{.}5550(4)$	$-19°00'39\overset{''}{.}466(18)$
VLBA	C	$07^h16^m34\overset{s}{.}5550(1)$	$-19°00'39\overset{''}{.}476(3)$
ATCA	C	$07^h16^m34\overset{s}{.}573(10)$	$-19°00'38\overset{''}{.}6(7)$
Subaru	i'	$07^h16^m34\overset{s}{.}556(7)$	$-19°00'39\overset{''}{.}53(8)$

Table 2. Radio and optical positions seven sources in the field-of-view. The uncertainties of the Subaru positions have the uncertainty in the astrometric calibration added in quadrature.

Telescope	Band	α_{J2000}	δ_{J2000}
Source 1 (NVSS J071639−185620)			
e-MERLIN	L	$07^h16^m39\overset{s}{.}408(2)$	$-18°56'29\overset{''}{.}93(3)$
e-MERLIN	C	$07^h16^m39\overset{s}{.}4080(5)$	$-18°56'29\overset{''}{.}89(2)$
VLBA	C	$07^h16^m39\overset{s}{.}4082(1)$	$-18°56'29\overset{''}{.}890(3)$
ATCA	C	$07^h16^m39\overset{s}{.}410(2)$	$-18°56'29\overset{''}{.}30(19)$
Subaru	i'	$07^h16^m39\overset{s}{.}408(7)$	$-18°56'30\overset{''}{.}06(9)$
Source 2 (NVSS J071604−190015)			
e-MERLIN	L	$07^h16^m04\overset{s}{.}037(2)$	$-19°00'15\overset{''}{.}78(3)$
e-MERLIN	C	$07^h16^m04\overset{s}{.}0370(6)$	$-19°00'15\overset{''}{.}86(3)$
VLBA	C	$07^h16^m04\overset{s}{.}0355(1)$	$-19°00'15\overset{''}{.}775(3)$
ATCA	C	$07^h16^m04\overset{s}{.}034(1)$	$-19°00'14\overset{''}{.}79(15)$
Subaru	i'	$07^h16^m04\overset{s}{.}030(7)$	$-19°00'15\overset{''}{.}83(8)$
Source 3			
e-MERLIN	L	$07^h16^m05\overset{s}{.}475(2)$	$-19°00'16\overset{''}{.}88(3)$
ATCA	C	$07^h16^m05\overset{s}{.}470(4)$	$-19°00'15\overset{''}{.}9(4)$
Subaru	i'	$07^h16^m05\overset{s}{.}467(8)$	$-19°00'16\overset{''}{.}78(10)$
Source 4			
e-MERLIN	L	$07^h16^m14\overset{s}{.}405(2)$	$-19°06'50\overset{''}{.}47(4)$
ATCA	C	$07^h16^m14\overset{s}{.}403(7)$	$-19°06'49\overset{''}{.}8(7)$
Source 5			
e-MERLIN	L	$07^h16^m02\overset{s}{.}558(3)$	$-19°08'19\overset{''}{.}89(4)$
Source 6			
e-MERLIN	L	$07^h16^m19\overset{s}{.}356(3)$	$-19°13'56\overset{''}{.}94(4)$
Source 7			
e-MERLIN	L	$07^h16^m47\overset{s}{.}200(3)$	$-18°45'25\overset{''}{.}26(5)$

Mooley et al. 2016) led Keane et al. (2016) to argue in favour of the association between FRB 150418 and the fading radio source, and hence with the galaxy.

The association of FRB 150418 with the fading radio source and hence with WISE J071634.59−190039.2 met with criticism. Karl G. Jansky Very Large Array (JVLA) observations of the persistent radio source in WISE J071634.59−190039.2 showed rapid variability, which led Williams & Berger (2016) to argue that the variability of the fading radio source is consistent with the intrinsic or scintillating behaviour of a compact, weak active galactic nucleus (AGN). Similarly, Akiyama & Johnson (2016) show that the variability of the persistent source may be extrinsic and attributable to refractive scintillation in the Milky Way, assuming a compact radio source is present in the galaxy. Vedantham et al. (2016) find a flat radio spectrum for the persistent source and suggest it is consistent with the properties of an AGN.

Since FRB 150418 is the first FRB for which a radio counterpart and host galaxy have been suggested, the host galaxy warrants closer study. In this Letter we report on an astrometric radio and optical analysis that establishes that WISE J071634.59−190039.2 currently contains a single weak, compact radio source consistent with an AGN located at the centre of the galaxy.

2 OBSERVATIONS AND ANALYSIS

2.1 ATCA

We observed WISE J071634.59−190039.2 with the ATCA on 2016 March 1 at 05:30 UTC for a duration of 11 h. Observations were made in 6B configuration, in two frequency bands each with bandwidth 2 GHz centred at 5.5 and 7.5 GHz, respectively. Single pointing mode was used which yielded an image rms of 6 μJy beam^{-1} with an angular resolution of 1.9 × 10.4 arcsec^2. Bandpass and flux density calibration were carried out using the standard ATCA calibrators B1934−638 and B0823−500 and phase calibration with B0733−174. Data reduction was performed in MIRIAD (Sault, Teuben & Wright 1995) using standard techniques and the position of sources in the field were measured using the task IMFIT. The position is listed in Table 1. In addition, we used the mosaic observations made with the ATCA on 2015 October 27 and described in Keane et al. (2016) to measure the positions of four other sources in the field (Table 2).

2.2 e-MERLIN

WISE J071634.59−190039.2 was observed with the e-Multi-Element Radio Linked Interferometer Network (e-MERLIN) array on 2016 March 18, 21, and 22 between 17:00 and 21:50 UTC on each day at C band (4.816–5.328 GHz). The e-MERLIN array comprised of six telescopes for each of these observations. The 76-m Lovell telescope was not included. Data were correlated in full Stokes mode in a standard C-band configuration with 4 × 128 MHz bands. The target and phase calibrator (J0718−1813) were observed with a 7:3 min phase referencing cycle. In addition, every hour, one target scan was re-deployed to observe a faint nearby NRAO VLA Sky Survey (NVSS) radio source (J0716−1908) in order to verify calibration. Observations of 3C 286 and OQ 208 (30 min each) were made for flux density and bandpass calibration.

Each observing run was reduced independently and in an identical manner. Data were imported into AIPS (Greisen 2003) using the e-MERLIN pipeline (Argo 2015). Following editing, these data were fringe-fitted for delay only and flux density calibrated using 3C 286 relative to the Perley & Butler (2013) flux density scale. Bandpass solutions were derived using the point source calibrator OQ 208. Standard phase referencing calibration was applied using the nearby phase calibrator source J0718−1813. These phase and amplitude calibration solutions were then applied to both the target and check calibration source (J0716−1908) which were subsequently imaged using standard techniques.

Following initial imaging of individual epochs, data from all three observing runs were concatenated together to increase sensitivity. These data were then re-weighted in a time and frequency dependent manner to maximize the sensitivity. An unresolved radio source associated with WISE J071634.59−190039.2 was detected with a measured peak brightness of 151 μJy beam^{-1} and an image rms of 21 μJy beam^{-1}. The angular resolution is 0.251 × 0.030 arcsec^2 at a position angle of $11\overset{\circ}{.}8$. In addition to the target source, two in-beam radio sources were detected. The coordinates of these sources and WISE J071634.59−190039.2 are listed in Tables 1 and 2.

In addition to these C-band observations, e-MERLIN also observed at L band (1.25–1.75 GHz) on 2016 April 2 between 16:15 and 21:00 UTC. These observations utilized all e-MERLIN telescopes including the Lovell telescope. Data were correlated across

512 MHz of bandwidth and divided in to eight bands. The same phase calibration source (J0718−1813) as employed at *C* band was used, and data were reduced in an identical manner.

Following wide field imaging of the target field at *L* band, e-MERLIN detected seven radio sources within the wider field of view accessible to the array. The positions of these sources are listed in Table 2. Radio emission at the location of the target source, WISE J071634.59−190039.2, was detected at a peak flux density of 92 ± 19 μJy beam^{-1}. The angular resolution is 0.46×0.32 arcsec^2 at a position angle of $-6\overset{\circ}{.}6$.

2.3 VLBA

The Very Long Baseline Array (VLBA; Napier et al. 1994) was used to observe WISE J071634.59−190039.2 on 2016 March 8, 00:30–06:30 UTC at *C* band (4.852–5.108 GHz). Data were recorded in dual circular polarization mode for 8×32 MHz bands with 2-bit Nyquist sampling, corresponding to an aggregate recorded data rate of 2048 Mbps. All 10 antennas of the VLBA were used. As well as the target galaxy, two phase reference sources were observed, J0719−1955 and J0718−1813 (same phase calibrator as used for e-MERLIN). Observations of each individual phase reference source were made once per 10 min, but interleaved such that a calibrator was observed every 5 min.

The data were correlated using the DIFX software correlator (Deller et al. 2007, 2011) using an integration time of 1.024 s and with 64 frequency channels per 32 MHz of bandwidth. As well as correlation phase centres set on the target galaxy and phase reference positions, additional phase centres (J2000) were correlated, for sources known from our ATCA imaging within the VLBA primary beam while pointed at the target galaxy. Four additional phase centres were correlated ($\alpha_{\rm J2000}$, $\delta_{\rm J2000}$): ($07^{\rm h}16^{\rm m}39\overset{\rm s}{.}41$, $-18°56'29\overset{''}{.}2$); ($07^{\rm h}16^{\rm m}04\overset{\rm s}{.}04$, $-19°00'14\overset{''}{.}7$); ($07^{\rm h}16^{\rm m}05\overset{\rm s}{.}47$, $-19°00'15\overset{''}{.}9$); and ($07^{\rm h}16^{\rm m}14\overset{\rm s}{.}41$, $-19°06'49\overset{''}{.}9$).

The correlated data were processed in AIPS (Greisen 2003) using standard phase reference techniques. System temperature and gain information for each antenna were used to calibrate the visibility amplitudes, in addition to corrections for sampler thresholds. Corrections for instrumental effects, Earth orientation parameters, and ionosphere were applied to the visibility phases. The data for the two phase reference calibrators were then fringe-fitted, exported from AIPS, and imaged in DIFMAP (Shepherd, Pearson & Taylor 1995). The images were imported to AIPS and used as source brightness models in a second round of fringe-fitting, to account for their structure contributions to the visibility phases. The resultant phase corrections were smoothed over a 0.4-h period using boxcar averaging. The final aggregate amplitude and phase corrections were transferred to the correlated data for each of the target and in-beam radio sources and applied to the visibilities before writing the data to disc as FITS files, retaining full frequency channelization.

The FITS files were read in to MIRIAD and naturally weighted Stokes *I* images (± 1.5 arcsec around the phase centre position) were produced, using multifrequency synthesis to avoid bandwidth smearing, with 0.3 mas pixel^{-1} sizes (10 000-pixel images). The target radio source associated with WISE J071634.59−190039.2 was detected with a peak brightness of 130 μJy beam^{-1} and an image rms of 14 μJy beam^{-1}. The position, obtained using task MAXFIT and checked with task IMFIT, is listed in Table 1. The uncertainty on the position includes the uncertainty on the position of the phase reference calibrators (<1 mas in both coordinates) as given by Petrov et al. (2006). No evidence of resolved emission is seen and the object appears point like (<1.5 mas in extent). The angular resolution (full width at half-maximum of the point spread function) of the VLBA images is 0.9×2.6 mas^2 at a position angle of $-3\overset{\circ}{.}4$. Two of the in-beam sources were also detected, and coincide with e-MERLIN and ATCA sources 1 and 2 (see Table 2).

2.4 Subaru

Optical observations of the field containing FRB 150418 were obtained with Suprime-Cam on the 8.2-m Subaru Telescope. Here, we use the i'-band observation obtained on 2015 April 19 with a dithered set of 10×60 s exposures. Suprime-Cam is a mosaic of ten 4k × 2k detectors, covering a field-of-view of 34×27 arcmin^2 sampled at 0.2 arcsec pixel^{-1}. The individual images were reduced using the Hyper-Suprime-Cam pipeline version 3.8.5, which is developed based on the Large Synoptic Survey Telescope (LSST) pipeline (Ivezic et al. 2008; Axelrod et al. 2010). Following the bias subtraction and flat-fielding, the astrometry of all images is simultaneously solved with a fifth-order polynomial to represent the optical distortion. Here we used 4606 stars for the fitting to the external catalogue and 3826 stars for the internal fitting. The weights of images for co-adding them are also derived according to their signal-to-noise ratios. Thereafter, the individual images were mapped to pixels on a world coordinate system and a weighted mean of each pixel value was computed with clipping of 3σ outliers.

To calibrate the astrometry of this co-added image, we compared the centroids of stars on a 14×14 arcmin^2 subsection with several astrometric catalogues. We selected only bright ($K < 14$) stars from the Two Micron All Sky Survey (2MASS) catalogue (Cutri et al. 2003; Skrutskie et al. 2006) that matched objects on the Suprime-Cam image that were not saturated and appeared stellar and unblended. Iteratively rejecting outliers with residuals in excess of 0.25 arcsec, the final astrometric calibration, fitting for zero-point position, and a four-parameter transformation matrix, uses 88 stars and yields rms residuals of $0\overset{''}{.}058$ in right ascension and $0\overset{''}{.}060$ in declination.

Since the 2MASS catalogue does not provide proper motions, the calibration might have a systematic positional offset due to non-random proper motions over the ∼15 yr time baseline between the 2MASS observations and the Subaru observation. To investigate the effect of proper motion we also calibrated the same subsection of the Suprime-Cam image against the 4th version of the USNO CCD Astrograph Catalog (UCAC4; Zacharias et al. 2013). This catalogue provides proper motions by combining positional CCD measurements obtained between 1998 and 2004 with positions from historic astrograph plates. Propagating the UCAC4 positions to the epoch of the Subaru observations, and applying the same procedure as with 2MASS, we obtain an astrometric calibration using 78 stars and rms residuals of $0\overset{''}{.}101$ in right ascension and $0\overset{''}{.}083$ in declination.

Based on the UCAC4 calibration, the centre of light of WISE J071634.59−190039.2 is offset from the position based on the 2MASS calibration by $0\overset{''}{.}047$ in right ascension and $0\overset{''}{.}025$ in declination. Since the UCAC4 calibration corrects for proper motion and encloses the positional uncertainty of WISE J071634.59−190039.2 based on the 2MASS calibration, we use the UCAC4 calibration for the remainder of the Letter. Of the seven additional radio sources detected by e-MERLIN at *L* band, six overlap with the full Subaru image, and three have optical counterparts above the 5σ limit of $i' = 24.7$. The positions of these counterparts and that of WISE J071634.59−190039.2 are given in Tables 1 and 2. The optical positions of these counterparts are

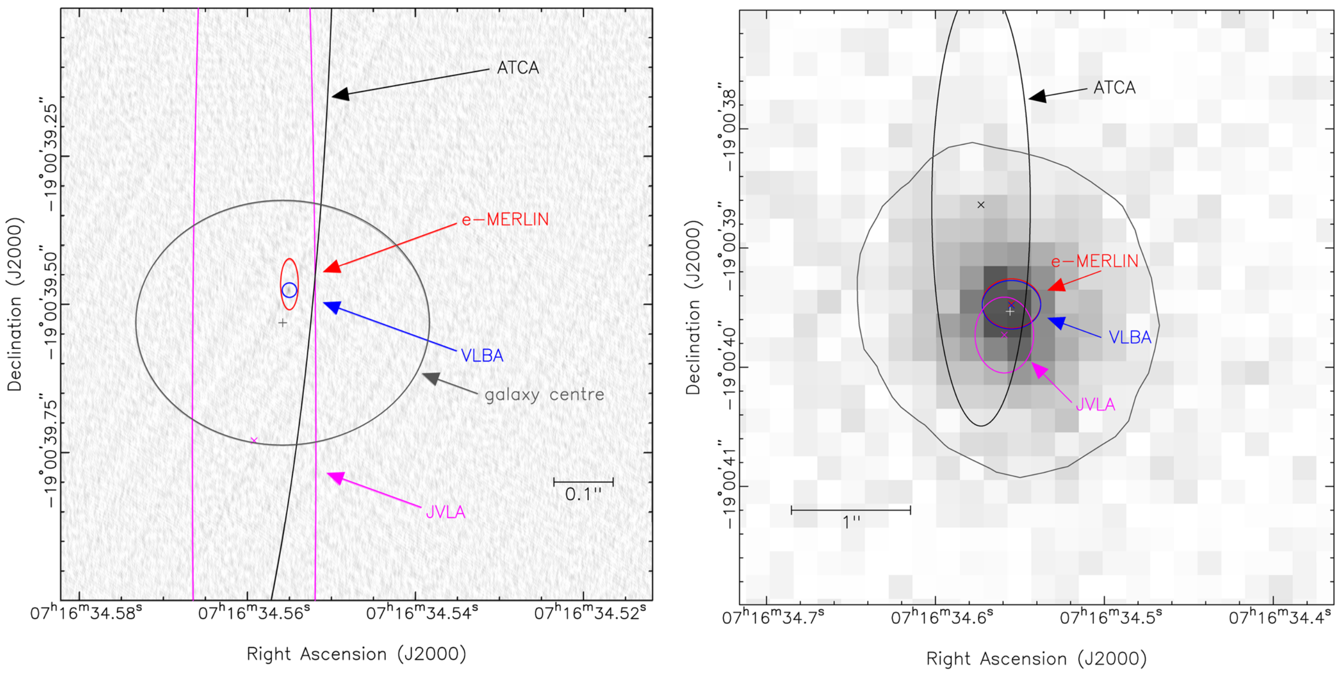

Figure 1. The left-hand panel shows a 1 × 1 arcsec^2 subsection of the VLBA radio image of the galaxy centre. Here, the position and uncertainty of the optical centre of the galaxy are shown with the plus sign and the ellipse (95 per cent confidence). The right-hand panel shows a 5 × 5 arcsec^2 subsection of the 600 s Subaru Supreme-Cam i'-band image of the WISE J071634.59−190039.2 galaxy. The centre of light of the galaxy on the image is marked by the white plus sign. The dark grey contour traces the half-light radius as defined by Keane et al. (2016). In both panels, the 95 per cent confidence uncertainties on the positions of the radio source seen by e-MERLIN, VLBA, ATCA, and JVLA (Vedantham et al. 2016) are shown with the ellipses. Note that in the right-hand panel, these include the uncertainty in the astrometric calibration of the Subaru image, hence the differences in error region sizes between the two panels.

consistent with the radio positions, providing independent confirmation that the astrometric calibration is correct.

3 DISCUSSION

A single unresolved radio source is detected in the ATCA, e-MERLIN, and VLBA observations of WISE J071634.59−190039.2. The source has a brightness of 130–151 μJy beam^{-1} at frequencies between approximately 4.8 and 5.3 GHz, consistent within the uncertainties. The coordinates derived from the ATCA, e-MERLIN, and VLBA observations are in agreement and are consistent with previously reported ATCA (Keane et al. 2016) coordinates. These detections are consistent with the low significance detection at the same position with the European VLBI Network (EVN), reported by Marcote et al. (2016a,b), after our high-resolution astrometry was first reported as an Astronomer's Telegram (Bassa et al. 2016). The JVLA position by Vedantham et al. (2016) is also consistent with our e-MERLIN and VLBA positions.

The coordinates of the compact radio source are plotted in Fig. 1 and are overlaid on the Subaru Suprime-Cam i'-band image of WISE J071634.59−190039.2 that was obtained on 2015 April 19, as well as the VLBA radio image. We conservatively plot 95 per cent confidence uncertainty regions of the radio source positions. The optical centre of light of WISE J071634.59−190039.2 is offset from the *C*-band VLBA and e-MERLIN positions by $\Delta\alpha = 0\farcs01(10)$ and $\Delta\delta = -0\farcs05(8)$. On this basis, our astrometry shows that, within the uncertainties quoted above, the location of the compact radio source is consistent with the optical centre of light of WISE J071634.59−190039.2 in the Subaru i'-band image.

The compact radio source detected recovers a very high percentage of the persistent flux density reported by Keane et al. (2016) and Vedantham et al. (2016), indicating that little, if any, extended radio emission exists. The upper limit to the size of the radio source of <1.5 mas (implying a brightness temperature in excess of 5 × 10^6 K), corresponds to a physical size of less than 0.01 kpc at a redshift of $z = 0.49$. An interpretation of the radio emission as due to a star formation region therefore appears highly unlikely as circumnuclear star formation regions (e.g. NGC 253; Lenc & Tingay 2006), those associated with merger activity (Engel et al. 2011), or jet-induced star formation regions (Salomé, Salomé & Combes 2015), are generally two orders of magnitude larger than our upper limit. Furthermore, the observed brightness temperature exceeds that expected from thermal radio emission processes associated with star formation regions. The location of the compact radio source is consistent with our best estimate of the centre of its host galaxy. Thus, our data are consistent with the existence of a weak radio AGN within the galaxy (see Guidetti et al. 2013 for a discussion of the existence of AGN in 'radio-quiet' galaxies).

While the emission of the persistent source can be shown to be compact on VLBI angular scales (milliarcseconds), interstellar scintillation requires structure which is compact on far smaller scales (microarcseconds; Macquart et al. 2013). Our ATCA, e-MERLIN, and VLBA observations cannot directly probe the required angular scales. Hence, the presence of a compact persistent radio source such as an AGN in WISE J071634.59−190039.2 allows the scenario proposed by Williams & Berger (2016) and Akiyama & Johnson (2016); that the fading radio source coincident in position with WISE J071634.59−190039.2 and coincident in time with FRB 150418 could be due to interstellar scintillation.

The best probe of the scintillation interpretation will come from extensive radio photometry measurements, as the signature of scintillation is well known and can be tested against the data (Akiyama & Johnson 2016). A careful analysis of all available flux density measurements of WISE J071634.59−190039.2 from the ATCA, JVLA, e-MERLIN, VLBA, EVN, and other facilities should reveal whether the variability properties of the compact radio source are consistent with intrinsic AGN variability or scintillation.

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