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ON ASSOCIATING FAST RADIO BURSTS WITH AFTERGLOWS

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ABSTRACT

A radio source that faded over 6 days, with a redshift $z \approx 0.5$ host, has been identified by Keane et al. (2016) as the transient afterglow to a Fast Radio Burst (FRB 150418). We report follow-up radio and optical observations of the afterglow candidate, and find a source that is consistent with an active galactic nucleus (AGN). If the afterglow-candidate is nonetheless a prototypical FRB afterglow, existing surveys limit the fraction of FRBs that produce afterglows to 0.25 for modulation-index $m = \Delta S/S \geq 0.7$, and 0.07 for $m \geq 1$, at 95% confidence. Afterglow associations with the barrage of bursts expected from future FRB surveys must satisfy constraints on the afterglow rate set by state of the art slow-transient surveys.

Subject headings: methods: statistical – astrometry – radio continuum: galaxies

1. INTRODUCTION

Fast Radio Bursts (FRBs) are millisecond-duration, intense ($\sim$ 1 Jy) GHz transients that have dispersion measures well in excess of expected Milky Way contributions (Lorimer et al. 2007; Thornton et al. 2013; Spitler et al. 2014; Burke-Spolaor & Bannister 2014; Ravi et al. 2015; Petroff et al. 2015; Masui et al. 2015; Keane et al. 2016). Extragalactic FRBs would represent a truly extraordinary class of radio emitter, likely corresponding to exotic, cataclysmic events (for e.g., Kashiyama et al. 2013; Lyubarsky 2014; Kulkarni et al. 2014; Cordes & Wasserman 2016). If FRBs originate at cosmological distances, studies of FRB samples will revolutionize our understanding of the intergalactic medium (e.g., McQuinn 2014; Zheng et al. 2014).

Localization of an FRB to a host galaxy will not only determine the distance-scale of FRBs, but will also provide vital clues to evidence their origin, and realize the anticipated diagnostic of the IGM. Keane et al. (2016, hereafter K16) promptly followed up a Parkes event, FRB 150418. The field was imaged using the Australia Telescope Compact Array (ATCA) in the 4.5–8.5 GHz band. The first observations began 2 hr post-burst. The subsequent four epochs were at 5.8 d, 7.8 d, 56 d, and 190 d post-burst. Two variable sources were identified: a potential Gigahertz-Peaked Spectrum (GPS) source, and one that faded by a factor of ∼2.5 by the third epoch (7.8 d).[2]

The latter source, identified with a redshift $z \approx 0.5$ galaxy, was interpreted by K16 to be the transient afterglow of FRB 150418. To clearly distinguish this event from hypothetical FRB afterglows, we will refer to it as K16flare. K16 used previous surveys for week-timescale variables and transients (e.g., Bell et al. 2015; Mooley et al. 2016) to determine a false alarm probability of $< 0.1\%$ of observing K16flare in their observations. K16 interpreted the light-curve of K16flare as being consistent with the radio emission sometimes observed following a short gamma-ray burst (Fong et al. 2015).

The association between FRB 150418 and K16flare, if true, would be a spectacular confirmation of the cosmological nature of FRBs, enabling their application to intergalactic-medium studies. However, even before the publication ink was dry, Williams & Berger (2016) reported persistent radio emission from the host galaxy of K16flare 11 months after the FRB, brighter than the final K16 measurement, and thus suggested that it was an example of common variability in Active Galactic Nuclei (AGN) and unrelated to the FRB. Given the potential importance of K16's discovery, we consider the matter worthy of closer investigation.

The paper is organized as follows. In §2, we present follow-up observations of the candidate FRB host galaxy with the Karl G. Jansky Very Large Array (JVLA), and the W. M. Keck Observatory. In §3 we explore the hypothesis that K16flare is an AGN unrelated to the FRB. In §4, we explore the consequences of the K16flare-FRB association asserted by K16. We present the implications of our study to future FRB afterglow searches in §5, and conclude with a summary in §6.

2. RADIO & OPTICAL OBSERVATIONS

On 2016 March 04 (MJD 57451) we undertook observations over the frequency range 1–18 GHz of K16flare with the JVLA (DDT program 16A-432). Our observations were conducted during a single 3.5 hr block. The JVLA was in the C configuration. We used standard wide-band continuum observing set-ups and 3C 147 to place our observations on the Perley-Butler flux-density scale (Perley & Butler 2013). The data were processed in CASA 4.5.2 with the standard

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[2] The flux densities reported by K16 at the five epochs are 270 ± 50, 230 ± 20, 90 ± 20, 110 ± 20 and $90 \pm 20\,\mu$Jy respectively.

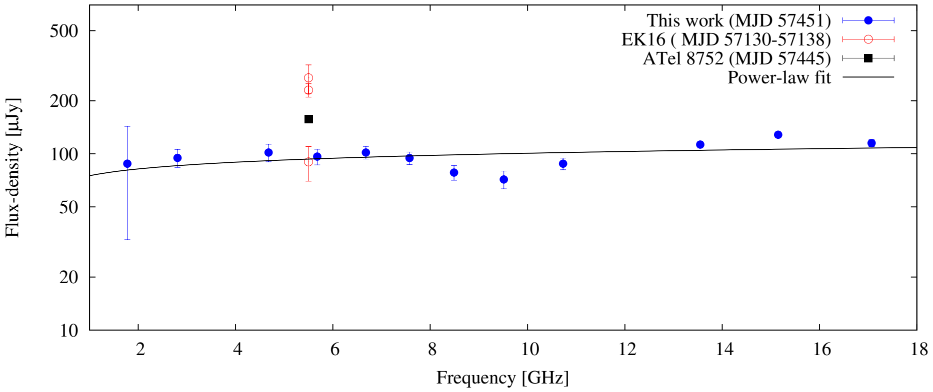

Figure 1. JVLA radio spectrum of host galaxy of K16flare, WISE J071634.59−190039.2 (blue circles), obtained on MJD 57451. The black line shows a best-fit power law spectrum to our data: $S_\nu = (100 \pm 5)\,[\nu/10\ \mathrm{GHz}]^\alpha$ with $\alpha = 0.13 \pm 0.10$. We also show C-band (5 GHz) flux density measurements obtained by K16 between MJD 57130 and 57138 (red open circles) and by Williams et al. (2016) on MJD 57445 (black square).

NRAO pipeline.[3] In the L-band (1.4 GHz) the image rms was 50 μJy whereas it ranged from 4 to 10 μJy across the S−Ku (2 GHz-18 GHz) band. We detected a point-like source across the entire decimetric band (Figure 1). The best-fit (Ku-band) position (J2000) is 07h16m34.5592(6)s, −19°00m39.73(1)s (1σ errors in the final significant figures in parentheses).

Separately, on MJD 57453, we observed the putative host galaxy (WISE J071634.59−190039.2) with the Low Resolution Imaging Spectrograph (LRIS Oke et al. 1995) mounted on the Keck I telescope. We obtained three exposures in the g and R optical bands with Keck-1/LRIS in imaging mode, totaling 610 s on MJD 57453. Observing conditions were good, with $0.75''$ R-band seeing. The data were initially processed using D. Perley's `lpipe` software.[4] Using an initial 10 s exposure, we obtained an initial astrometric solution from the USNO-B2 catalog using D. Perley's `autoastrometry.py` software, and refined the astrometry using stars with Ks magnitudes between 10−14 from the 2MASS Point Source Catalog (PSC; Skrutskie et al. 2006). The PSC astrometric accuracy is 70–80 mas: we assume a $0.1''$ (1σ) astrometric accuracy to account for possible minor distortion in the image. We then corrected the astrometry of our two 300-s exposures using the shallow exposure, and co-added the images. We obtained a deep Ks-band image of the field observed by M. Kasliwal (and presented in K16). An overlay of the radio position on the final R-band and K-band images is shown in Figure 2.

3. K16FLARE AS A VARIABLE AGN

Williams & Berger (2016) note that the radio luminosity measured by K16, and the near-infrared colors of the host galaxy WISE J071634.59−190039.2, are consistent with that of a low-luminosity AGN. We note that the radio source continues to vary even a year after the FRB. Williams et al. (2016) reported a flux-density of 157 ± 6μJy (5 GHz band; 2016 Feb 27/28). Our observations taken only six days later find the source to have decayed to 96±8 μJy. The modulation index[5] between the two runs is $m = 0.5 \pm 0.1$. For comparison, the maximum two-epoch modulation index of K16flare in the K16 observations was $m = 1.0 \pm 0.3$. Variability of $m \lesssim 1$ has been seen in other AGN (Mooley et al. 2016).

It is not uncommon for elliptical galaxies without any indication of an optical signature of nuclear activity to harbor a nuclear black hole, with low accretion rate, accompanied by low radio luminosity (e.g., Hodge et al. 2008). Variable radio emission in the $\gtrsim 5$ GHz band is attributed to emission regions at milli-arcsecond scales, and physically to relativistic shocks of compact jets (Bignall et al. 2015). Indeed, it was keeping this issue in mind that we designed our JVLA observations. The spectrum seen in Figure 1 is flat across this entire band (1–18 GHz) and consistent with that seen in several known AGN samples (Herbig & Readhead 1992; Kovalev et al. 2002). A flat spectrum is a key signature of an AGN core. The bumps are suggestive of multiple,

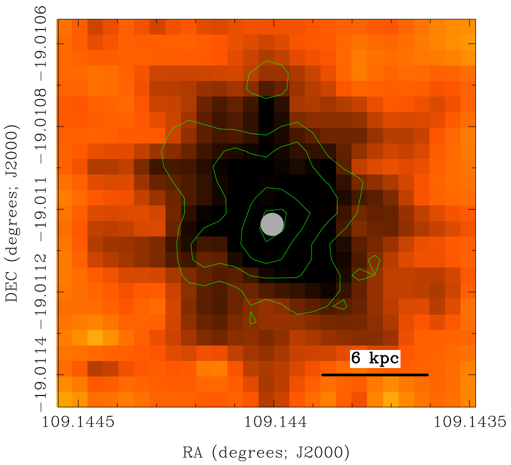

Figure 2. Overlay of the Ku-band radio position of the source (grey circle, with $0.1''$ radius; see §2) on a Ks-band image of WISE J071634.59−190039.2 which in turn was tied to the LRIS R-band image. The contours refer to the LRIS R-band image (levels: $[3, 5, 7, 9]\sigma$). The scale bar corresponds to 6 kpc at a redshift of 0.492, assuming cosmological parameters measured by the *Planck* mission.

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[3] https://science.nrao.edu/facilities/vla/data-processing/pipeline.

[4] http://www.astro.caltech.edu/∼dperley/programs

[5] We use the definition of Mooley et al. (2013): $m = 2|S_1 - S_2|/(S_1 + S_2)$, where S_1 and S_2 are the flux-densities at the two epochs.

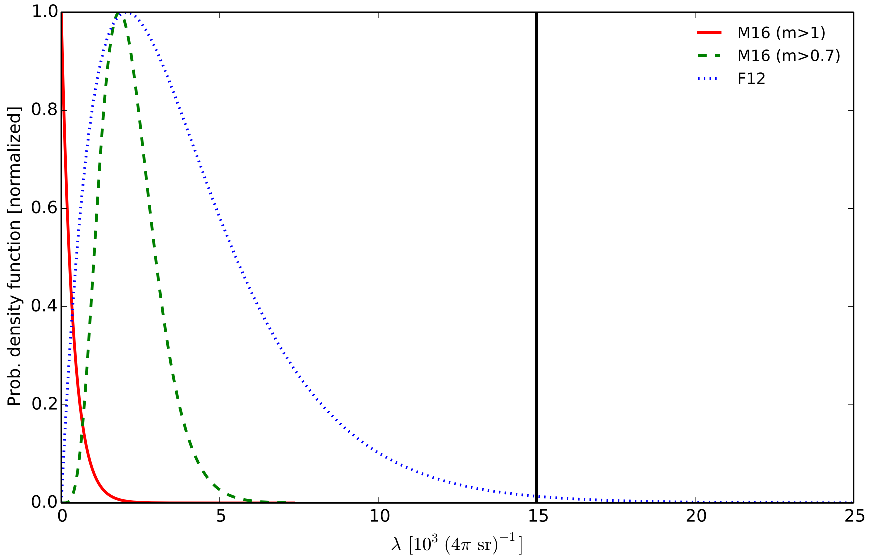

Figure 3. Posterior probability density function for the areal density of afterglows, λ, from slow-transient surveys. The completeness limit is $270\,\mu$Jy at 5.5 GHz. The black vertical line represents the all-sky afterglow rate for an FRB rate of $2500\,\mathrm{sky}^{-1}\,\mathrm{day}^{-1}$, and an afterglow duration of 6 days. K16flare has an m-value of 1 ± 0.3.

compact, optically thick synchrotron components.

Furthermore, as can be seen from Figure 2 the radio source coincides with the light centroid of the putative host galaxy to within experimental errors, $\lesssim 0.1''$.

The simplest hypothesis explaining (i) the persistence of a $\approx 100\,\mu$Jy flat-spectrum source nearly a year after the K16 observation of K16flare, (ii) its continued variability on 6-day timescales, and (iii) the nuclear origin, is that WISE J071634.59−190039.2 hosts a nuclear black hole accreting at a low rate. This hypothesis implies that K16flare was an example of AGN variability and unrelated to the FRB. Despite this apparently compelling conclusion, in the next section we explore observational constraints on possible radio afterglow emission from FRBs from existing radio surveys for transients and variables.

4. K16FLARE AS THE FRB 150418 AFTERGLOW

In the absence of any additional insight, we assume that K16flare is a prototypical FRB afterglow ($S \approx 270\,\mu$Jy at 5.5 GHz, spectral index of -0.7 at maximum). We use the VLA radio variability surveys of Mooley et al. (2016, hereafter M16) and Frail et al. (2012, hereafter F12) to search for FRB afterglows. Details of these two surveys can be found in the Appendix. We adopt a conservative all-sky FRB rate of $2500\,\mathrm{day}^{-1}$ for fluence $\mathcal{F} > 2$ Jy ms (Keane & Petroff 2015).

Since each FRB afterglow lasts 6 days, the expected slow-transient rate from FRB afterglows is $0.364\,\mathrm{deg}^{-2}\,\mathrm{epoch}^{-1}$. In the framework adopted for this section, namely all FRBs have radio afterglows similar to K16flare, the 50-square degree 3-epoch 3-GHz survey of M16 should have yielded about fifty five afterglows. They found none with $m \geq 1$, and five with $m \geq 0.7$. Next consider the the 944-epoch, $0.0225\,\mathrm{deg}^2$ slow-transient 5-GHz survey analyzed by F12. F12 should have seen eight afterglows; they found just one. Even with the conservative all-sky FRB rate of Keane & Petroff (2015), the discrepancy between the expectation and observations is large.

In Figure 3 we display the posterior probability density functions of the areal density of radio sources which vary on timescales of a week. The black vertical line shows the expected areal density of FRB afterglows assuming that all FRBs generate 6-day afterglows similar to K16flare. Even if FRBs are the only channel to create 6-day afterglows, the slow-transient surveys limit the fraction of FRBs that produce ($S \geq 270\,\mu$Jy) afterglows to < 0.25, for $m \geq 0.7$, and < 0.07 for $m \geq 1.0$ with 95% confidence. Therefore, if FRBs produce afterglows, based on measured average slow-transient rate, K16 had a $\lesssim 10\%$ chance of seeing an afterglow to FRB 150418.

5. GUIDANCE FOR FUTURE FRB AFTERGLOW SEARCHES

Our experience with FRB 150418 (K16flare) has informed us of the potential pitfalls in associating FRBs with afterglows. The areal density of 6-day FRB afterglows at any given epoch ranges from 0 (FRBs are not associated with afterglows) to $0.37\,\mathrm{deg}^{-2}$ (all FRBs are associated with afterglows). Depending on the fraction f of FRB associated with afterglows, FRB-afterglows can therefore form an insignificant part of the transient sky, or completely dominate it. New surveys such as the VLA Sky Survey (Myers et al. 2014) will systematically explore the sub-mJy transient sky in the decimetric band, better measuring the event background against which FRBs afterglows will be searched for.

Machines of the future such as CHIME (Bandura et al. 2014) and UTMOST (Caleb et al. 2016) are expected to discover a barrage of FRBs ($\gtrsim 1\,\mathrm{day}^{-1}$). Large FRB samples, combined with follow-up observations for which the background event rate is well known, will enable a direct measurement of the fraction f of FRBs that are associated with transient afterglows. If the transient background rate is $\lambda_{\rm bg}\,{\rm deg}^{-2}$, and FRBs are localized to Ω deg^2, the detection of m afterglow candidates in N follow-ups will yield the estimate $f = m/N - \lambda_{\rm bg}\Omega$. Based on Poisson statistics, the 1σ error in f will be $\approx \sqrt{m}/N$ for large m. Detection of m=100 transients in follow-ups for instance, will constrain f with about 10% fractional error (1σ).

While a statistical argument for FRB-afterglow association based on a large number of FRB follow-ups will be compelling, localization of an FRB itself at a few arcsecond-level would imply an (almost) absolute confirmation of the host galaxy. To this end, we have proposed and intend to build a $\gtrsim$10-element small dish array at the Owens valley radio observatory to both detect the brightest FRBs and provide a localization accuracy adequate for secure identification of host galaxies.

6. SUMMARY

We conducted radio and optical follow-up observations of the afterglow candidate to FRB 150418 (K16flare). We detected persistent radio emission from the host galaxy of K16flare $\sim$ 1 year after the FRB, which is nuclear in origin ($0.1''$ astrometric precision), and has a flat radio spectrum (1–18 GHz). It is consistent with an AGN core, and does not present prima facie evidence of being associated with FRB 150418.

If K16flare is nonetheless a prototypical FRB afterglow, existing slow radio transient surveys limit the fraction of FRBs that produce afterglows to < 0.25 for modulation indices ($m = \Delta S/\bar{S}$) of $m \geq 0.7$, and < 0.07 for $m \geq 1.0$ (95% confidence). The high areal density of FRBs must be accounted for in computing the statistical evidence for FRB-afterglow associations. Inferences on the fraction of FRBs that are associated with afterglows, of any kind, must be consistent with the rates of such events measured by state of the art blind surveys.

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APPENDIX

A1: LIMITS FROM SLOW-TRANSIENT SURVEYS

Afterglows probably emanate from expanding relativistic plasma where synchrotron self-absorption may be important. For this reason, apart from the M16 survey (2–4 GHz) which K16 consider in their false-positive rate calculation, we also consider limits on the transient areal density at 5 GHz by Frail et al. (2012, hereafter F12). F12's survey is at a similar frequency as the K16 afterglow, and has undergone rigorous tests to rule out false-candidates due to imaging and interference-related artifacts[6]

The relevant survey parameters and findings are summarized in Table 1. M16 report a 3-epoch 50 deg^2 survey, and classify variables by their m-values: $m = 2|S_1 - S_2|/(S_1 + S_2)$; S_1 and S_2 are flux-densities between epochs. The m-value for the K16 afterglow is $m = 1 \pm 0.3$. The M16 survey has a completeness limit of $S = 500\,\mu$Jy at 3 GHz, or $327\,\mu$Jy at 5.5 GHz assuming the same spectral index as the K16 afterglow. M16 found no transients, no variables with $m \geq 1$, and 5 variables with $m \geq 0.7$. M16 list a total of 10 variables (their Table 3) with $m \geq 0.7$, but half of them are grossly inconsistent with the K16 afterglow; their flux density drops and rises again on a 1 month timescale.

The F12 survey had a completeness limit of $S = 300\,\mu$Jy at 5 GHz ($280\,\mu$Jy at 5.5 GHz), and found just 1 transient; RT 19970528 was seen in their single-epoch search and faded from $1731 \pm 232\,\mu$Jy to $< 37\,\mu$Jy within 7 days. As such, it is similar to the K16 afterglow in its duration, but significantly brighter.

To compare the survey limits and the K16 afterglow on equal footing, we have: (i) computed a '5.5 GHz equivalent' completeness limit assuming a spectral index of -0.7, (ii) obtained the 95% confidence limits on the Poisson parameter λ in units of $(4\pi\,{\rm sr})^{-1}$, and finally (iii) scaled the limits to a completeness flux-density of $270\,\mu$Jy by assuming a uniformly distributed population in Euclidean space. The final limits on λ are presented in the last column of Table 1 and in Figure 3. These limits on the slow-transient areal density are valid for *any* afterglow, FRB-related or otherwise.

A2: AFTERGLOW RATE CALCULATION

Let N_a be the number of FRBs expected within the slow-transient survey area per day. Let each FRB afterglow last τ_a days. According to K16, $\tau_a \approx 6$ days. Let the slow-transient survey cadence be τ_s days. The total numbers

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[6] The Frail et al. (2012) results were obtained by reprocessing a dataset original presented by Bower et al. (2007).

Table 1
Parameters of the M16 and DF12 slow-transient surveys. FoV is the field of view; N_e is number of survey epochs; N_{det} is the number of transients or variables detected; m is the modulation index: $m = 2|S_1 - S_2|/(S_1 + S_2)$; λ is the Poisson rate parameter scaled to a completeness-limit of 270μJy at 5.5 GHz.

Survey	FoV [deg^2]	N_e	N_{det}	95% CL on λ [$(4\pi\text{sr})^{-1}$]
M16 ($m \geq 1$)	52	3	0	0^{+1099}_{-0}
M16 ($m \geq 0.7$)	52	3	5	1834^{+2021}_{-1111}
DF12	0.0225	944	1	2058^{+7706}_{-1953}

of FRB afterglows potentially detectable in a survey with N_e epochs is then $N_{agl} = N_e N_a \text{Min}(\tau_a, \tau_s)$ where Min(.) returns the smallest argument.

Since for both the M16 and F12 surveys $\tau_s > \tau_a$, the expected *all-sky* FRB afterglow rate is $N_e \tau_a \times$ (FRB all-sky rate). If all FRBs produce an afterglow similar to the one reported by K16, then for an FRB rate of $2500\,\text{sky}^{-1}\,\text{day}^{-1}$, the expected number of *detectable* afterglows in the M16 and F12 surveys are 55 and 8 respectively.

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