Fast Radio Bursts (FRBs) are bright millisecond radio transients with dispersion measure (DM) much larger than the values expected for the Milky Way galaxy, so that they are expected to have an extragalactic origin. Keane et al. (2016) reported the discovery of a fading radio transient following FRB 150418 starting from 2 hours after the FRB, which faded away in 6–8 days. They claimed that the radio transient is the afterglow of FRB 150418, and interpreted it as the afterglow of the FRB. Williams & Berger, on the other hand, suggested that the radio transient is analogous to a group of variable radio sources, so that it could be a coincident AGN flare in the observational beam of the FRB. A new observation with VLA showed a re-brightening, which is consistent with the AGN picture. Here, using the radio survey data of Ofek et al., we statistically examine the chance coincidence probability to produce an event like the FRB 150418 transient. We find that the probabilities to produce a variable radio transient with at least the same variability amplitude and signal-to-noise ratio as the FRB 150415 transient, without and with the VLA point, are $P_1 \sim 6 \times 10^{-4}$ and $P_2 \sim 2 \times 10^{-5}$, respectively. In addition, the chance probability to have a fading transient detected following a random time (FRB time) is less than $P_2 \sim 10^{-2.9\pm1.3}$. Putting these together and assuming that the number of radio sources within one Parkes beam is 16, the final chance coincidence of having an FRB 150418-like radio transient to be unrelated to the FRB is $<10^{-4.9\pm1.3}$ and $<10^{-4.4\pm1.3}$, respectively, without and with the VLA point. We conclude that the radio transient following FRB 150418 has a low probability being an unrelated AGN flare, and the possibility of being the afterglow of FRB 150418 is not ruled out.
which lists all the observation results). In order to compare
with the observation of FRB 150418 afterglow candidate [Keane et al. (2016)], we randomly select the
same number of observational epochs as FRB 150418
for each source, and calculate the relative standard de-
viation STD/(f) as well as median signal-to-noise ratio
S/N. We do it 1000 times for each source, so that we
have 464,000 simulated mock observations. Similar to
Fig. 2 of Williams & Berger (2016), we present the S/N-
STD/(f) two-dimensional distribution of these mock
events in the right panel of Figure 1. For the sake of
clear presentation, only a random set of 4,640 mock
events are shown. For comparison, the FRB afterglow
candidate, which has STD/(f) = 0.54 and median S/N
= 5.4 with the observational data of Keane et al. (2016),
is also marked as the red star in the right panel of Fig.
1. Williams & Berger (2016) reported an observation of
the FRB host on 2016 Feb 27 and 28, which has a flux 0.157
± 0.006 mJy/beam. By including this point, the FRB af-
fterglow candidate has STD/(f) = 0.48 and median S/N
= 5.5. It is shown as the orange star in the right panel of Fig. 1.

An immediate observation from Fig. 1 is that a large
STD/(f) tends to appear for small S/N values. At the
S/N for FRB 150418, the observed STD/(f) in general
is much smaller than that of the FRB 150418 tran-
sient. Williams & Berger (2016) argued that the tran-
sient source is consistent with the distribution of the
Ofek et al. (2011) sources. However, we argue that it
is more important to check the chance probability to
have a variable source with both STD/(f) and S/N at
least the values inferred from the FRB 150418 tran-
sient. From our mock sample, the fraction of events
that have STD/(f) larger than STD/(f)FRB and me-
dian S/N larger than S/NFRB for the Keane et al. (2016)
data only (without the late VLA point of Williams et al.
2016) turns out to be P1 ∼ 6 × 10−4. It indicates that the
average number of events which could be as bright as
the FRB transient in the Parkes beam by chance is
Nr ∼ NFRB · P1 ∼ 0.009. Adding the latest VLA observa-
tional point Williams et al. (2016), this fraction is in-
creased to P1 ∼ 2 × 10−3, and the variable number be-
comes Nr = NFRB · P1 ∼ 0.06. Therefore, even if the radio
variable source may be common, the chance probability
of having a high-variability radio transient similar to the
putative FRB 150418 afterglow within the FRB 150418
Parkes beam is small.

We also try to compare the FRB afterglow candidate
with Mooley et al. (2016), who monitored a larger sky
area and have more radio sources in their catalog. Since
there are only two observational points in week timescale
for each source in Mooley et al. (2016), we choose the
first observational point of Keane et al. (2016), i.e. 0.27±
0.05 mJy, and the quiescent flux 0.09 ± 0.02 mJy, to
compare with those in Mooley et al. (2016). Using the
distribution of m = SFRB, analogous to STD/(f)FRB, and
V = S/NFRB, analogous to median S/N, as shown in Figure
10 of Mooley et al. (2016), we find that there is no source
in Mooley et al. (2016) that is as significant as this FRB
afterglow candidate. If we change the second point to
0.11 ± 0.02, the fraction of sources as significant as the
FRB afterglow candidate is 0.001. This is consistent with
our previous result.

3. TEMPORAL COINCIDENCE PROBABILITY

The existence of an event with a similar STD/(f) and
median S/N to the FRB 150418-transient does not necessarily interpret the observation. One impor-
tant, intriguing fact is that the radio source was fading
during the span of the 5 ATCA observations (left panel of Fig. 1), which have observational epochs at
to + [0.09, 5.9, 7.9, 78.7, 193.4] days after the FRB time
t0, respectively, for the Keane et al. (2016) observation.
Assuming that during 190 days there was only one bright
transient (i.e. there is no variability during the last three
observational epoch), the duty cycle of flares may be es-
imated as ∼ 8 days /190 days ∼ 0.04. the chance of
having the first observation to be the brightest point is
P2 ∼ 0.09/190 ∼ 5 × 10−4.

One may argue that the source may be variable all
the time, and that the first observation may have missed
even brighter phases at earlier times. In order to examine
these probabilities, we perform a Monte Carlo simulation
using the most conservative approach by assuming that
the source has a variability duty cycle of 100%.[1] We
assume that the source varies sinusoidally with time, i.e.

\[ f = f_0 + A \sin(2\pi t / P) \]

but with the amplitude A varying in different periods. Here
f0 is the flux of the quiescent state. Since the period P
is unknown, we vary it from 2 days to 100 days. By fix-
ing a particular P, we simulate a mock light curve
which lasts for 500 periods. We allow the amplitude A
to be variable. For each period, it is randomly simulated
based on the STD/(f) distribution in the Ofek et al.
(2011) catalog. For a sinusoidal distribution, one has

\[ A = \sqrt{2}\text{STD}, \quad (f) = f_0. \]

In order to be consistent with the observed FRB afterglow, the STD/(f) distribution with median S/N = (5 − 6)
is used. An example of a small passage of the simulated light curve is shown in the left panel of Figure 2.

From each simulated light curve, we randomly pick a t0
time as the epoch of the FRB, and then pick up the fluxes
at the time series t0 + [0.09, 5.9, 7.9, 78.7, 193.4] days as a
simulated detection series. We require that the resulting
light curve should statistically decrease with time with
respect to the first point. We simulate 106 FRBs in each
light curve and estimate the fraction of simulated detec-
tion series that satisfy the above criterion. The fraction
as a function of the assumed period is shown in the right
panel of Figure 2. It can be seen that, the fraction of the
simulated detection series that satisfy the monotonic
condition P2 is period dependent. In general, the larger
the period is, the less possible to produce a detection se-
ries similar to the FRB 150418 transient. By accounting
for the range of P2 introduced by the period-dependence,
we finally get P2 = 10^{−2.9±1.3}, with the latest probability
P2,max ∼ 0.14 (corresponding to period P ∼ 23 days).

1 By introducing a smaller duty cycle, our simulations suggest
that the chance probabilities for the temporal coincidence are in-
deed even lower.
In reality the variable source is not strictly periodic. We also tried to simulate light curves with a distribution of period within each light curve. Both a uniform distribution and a Gaussian distribution of $T$ are tested. The mean value of $P_2$ is slightly larger, but the scatter becomes smaller, with the largest probability $P_{2,\text{max}} \sim 0.01$.

Combining all the constraints (spatial, flux, and temporal coincidence), the final chance probability to have an unrelated AGN flare to mimic the putative afterglow of FRB 150418 is

$$P = N_1 P_1 P_2,$$

which is $\sim 10^{-4.9 \pm 1.3}$ for the original Keane et al. (2016) data, and is $\sim 10^{-4.4 \pm 1.3}$ with the inclusion of the latest VLA data (Williams et al. 2016) (see Table 1). Both are very small numbers.

4. COMPARISON WITH SHORT GRB RADIO AFTERGLOWS

Since the putative afterglow of FRB 150418 has a flux comparable to that of short GRBs (Keane et al. 2016; Zhang 2016), it is worth comparing the variability properties of short GRB afterglows with the FRB 150418 transient. There are two SGRBs with at least two radio afterglow detections. One is GRB 050724 from the radio afterglow catalog of Chandra & Frail (2012). Another one is GRB 130603B, which has two detections and two upper limits (Fong et al. 2014). Following the same procedure, we present their $\text{STD}/\langle f \rangle$ and median $S/N$ in Table 1. Assuming that they fall into one of the Parkes beams, we calculate the chance probability of confusing them with an underlying AGN radio flaring sources in the Ofek et al. (2011) catalog. The afterglow light curves of the two short GRBs are presented along with that of FRB 150418 in the left panel of Fig. 1 (in green and blue). Upside down triangles indicate upper limits. In the process of estimating $\text{STD}/\langle f \rangle$ and median $S/N$ for the two short GRBs, we treat the upper limits in two different methods: one is to include them by assuming that both detection values and the errors are half of the upper limit values; the other is to exclude the upper limits completely. These two methods define a range of $\text{STD}/\langle f \rangle$ and median $S/N$, which are marked in the right panel of Fig. 1 as segments connected with two filled circles. The results with the first method are marked with small circles, and those with the second method are marked with large circles. One can see that GRB 050724 has a more significant variability and a smaller chance probability than FRB 150418. On the other hand, GRB 130603B is less variable and has a similar chance probability to be confused as a flaring source as FRB 150418. In general, FRB 150418 sits near the two short GRBs in the $\text{STD}/\langle f \rangle$ - $S/N$ space, suggesting that the data are not inconsistent with being an FRB / short GRB afterglow, as suggested by Keane et al. (2016).

5. CONCLUSIONS AND DISCUSSION

We have statistically examined the probability of having a random variable source, such as AGN, following FRB 150418 by comparing the event with the radio variable sources presented in Ofek et al. (2011). By requiring that the coincident transient should have at least the same $\text{STD}/\langle f \rangle$ and median $S/N$ values as the FRB 150418 transient and that it should decay starting from the first observation, the combined spatial, flux, and temporal chance coincidence probability is $< 10^{-4.9 \pm 1.3}$ for Keane et al. (2016) observational data only, and <


Fig. 2.—Left: A passage of one simulated lightcurve. Right: The fraction of simulated detection series similar to FRB afterglows (monotonously decreasing) as a function of the assumed period.

| Table 1: Probability to reproduce FRB/SGRB radio afterglows by a chance coincidence |
|---------------------------------|----------------|----------------|----------------|----------------|
| FRB 150418 (Keane et al. (2016)) | 0.54 \pm 0.2 | 5.4 \pm 5.5 | 16 | 6 \times 10^{-4} | 10^{-4.2 \pm 1.3} | 10^{-4.4 \pm 1.3} |
| FRB 150418 (Keane et al. (2016); Williams et al. (2016)) | 0.48 \pm 0.2 | 5.5 \pm 5.5 | 16 | 2 \times 10^{-3} | 10^{-4.2 \pm 1.3} | 10^{-4.4 \pm 1.3} |
| GRB 050724 (with upper limits) | 0.85 | 5.2 | 4.3 \times 10^{-5} |
| GRB 050724 (without upper limits) | 0.63 | 5.5 | 2 \times 10^{-4} |
| GRB 130603B (with upper limits) | 0.95 | 4.3 | 1 \times 10^{-4} |
| GRB 130603B (without upper limits) | 0.45 | 6.5 | 7.8 \times 10^{-4} |

Note: Column 1: FRB/GRB names; Column 2: relative standard deviation. STD is the standard deviation and \( f \) is the average flux. Column 3: median signal to noise ratio; Column 4: estimated number of radio sources within one Parkes beam; Column 5: probability to reproduce one event as significant as the FRB afterglow candidate (with both STD/\( f \) and median S/N larger than those of the FRB afterglow candidate) with the observational data of Ofek et al. (2011); Column 6: probability upper limit to have a fading event by chance, with a 100% duty cycle assumed; Column 7: overall probability to have the FRB afterglow candidate originating from chance coincidence.

10^{-4.4 \pm 1.3} with the VLA point included (Williams et al. 2016). We also show that the event is not inconsistent with a short GRB radio afterglow (with host contamination). We therefore argue that the event has a low probability being an unrelated AGN flare, and that the possibility that the source is the intrinsic afterglow of FRB 150418 is not ruled out by the current data. Further monitoring the source is needed to place more constraints on the afterglow and AGN possibilities. If the source later re-brightens to the level of the first two data points of Keane et al. (2016), then the afterglow scenario would be ruled out. A smaller variability as seen by Williams et al. (2016), would not significantly alter the conclusion of this paper, since scintillations (Hughes et al. 1992; Qian et al. 1995; Goodman 1997) would explain such fluctuations as long as the emitting region has a small enough angular size.

Suppose that the first two data points following FRB 150418 are indeed the afterglow of the FRB, the existence of a bright radio host is still puzzling. One may consider the following possibilities.

1) First, the host may be related to the star formation in the host. Assuming that the quiescent radio emission of the host originates from star formation, the star formation rate (SFR) estimated with radio emission is 10^{1.7} M_\odot yr^{-1} (Kennicutt & Evans 2012), two orders of magnitude larger than the upper limit estimated from Ha emission line (Keane et al. 2016). It indicates an inconsistency between the emission line-estimated SFR and the continuum-estimated SFR. Such a discrepancy also occasionally seen in SGRB hosts. For example, the host of GRB 050509B, which is an elliptical galaxy, also shows no SFR by using emission lines as an indicator, < 0.1 M_\odot yr^{-1} (Berger 2009), while the SFR estimated by UV emission is 16.9 M_\odot yr^{-1} (Savaglio et al. 2009). Although such a possibility is not ruled out, it is not favored. Within this picture, the host flux is not expected to fluctuate significantly. If the VLA rebrightening reported by Williams et al. (2016) is not due to a mis-calibration between VLA and ATCA, it strongly disfavors this possibility.

2) Second, the quiescent radio flux is from an underlying low-activity AGN, while the FRB is related to a compact-star merger event (Zhao et al. 2016) within the host galaxy of the AGN. This is not impossible, since the host galaxy appears as an elliptical galaxy with little star formation, which is consistent with being a host of compact star mergers (Gehrels et al. 2003; Barthelmy et al. 2005; Berger 2014). The probability of having such a weak AGN host may be low, and is worth investigating. As an elliptical galaxy with a stellar mass 10^{11} M_\odot (Keane et al. 2014), the central black hole mass of the putative FRB host may be estimated using the M_{BH} - M_\star relation (Haring & Rix 2004), which gives
$M_{\text{BH}} = 10^{8.2} M_\odot$. If the radio quiescent emission is truly from the central black hole, it indicates a radio luminosity $4.2 \times 10^{39}$ erg/s. The X-ray luminosity anticipated from the black hole activity fundamental plane is $1.4 \times 10^{43}$ erg/s, which is smaller than the X-ray upper limit from Swift (Keane et al. 2016). Although the optical spectrum of the host disfavors an AGN at the center, it is supported by the consistency between its radio spectrum and those of AGNs (Vedantham et al. 2016). It may be an low luminosity AGN or radio analog to the X-ray bright Optical galaxy (XBONG) (Yuan & Narayan 2004). Deep X-ray monitoring might be the best way to investigate the AGN possibility, and the origin of the radio quiescent emission of the host. In any case, the existence of an AGN does not rule out the possibility that the first two data points are due to the FRB 150418 afterglow.

(3) The third probability is that both afterglow and AGN are true (similar to the second possibility), but the FRB may be related to the AGN itself. However, no viable FRB model has been proposed to be produced in an AGN environment. One difficulty would be the time scale. Whereas the shortest time scale for a supermassive BH may be hours, the typical FRB duration is at most milliseconds. More work is needed to explore this possibility.

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